THE UNIVERSITY OF ALBERTA

BASAL BELLY RIVER SANDSTONE (UPPER CRETACEOUS), PEMBINA FIELD, ALBERTA, CANADA

A THESIS

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ABSTRACT

The basal Belly River sandstone in the Keystone area of the Pembina oil field, is part of a progradational sequence consisting of marine shale at the base, through beach sandstone to continental (lagoonal) coal beds at the top, deposited along the regressing shoreline of the Lea Park sea. The sandstone was deposited as a complex of bodies (probably bars or barrier beaches) which are relatively thick and clean in the central portion and thin and silty or shaly around the periphery. The topography that existed prior to the deposition of the complex does not seem to have controlled the sand distribution.

The behavior of the spontaneous potential in wells which penetrated the sandstones studied is normal except for tight calcite-cemented sandstone streaks which tend to reduce the spontaneous potential response.

The accumulation of hydrocarbons in the sandstone bodies is stratigraphic in nature, independent of structure, and is related to facies change from sandstone to shale.

ACKNOWLEDGEMENTS

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Messrs. D. R. Grant, G. H. Gowan, and B. Mark drafted the figures and Mrs. Ruth Smith typed the final manuscript.

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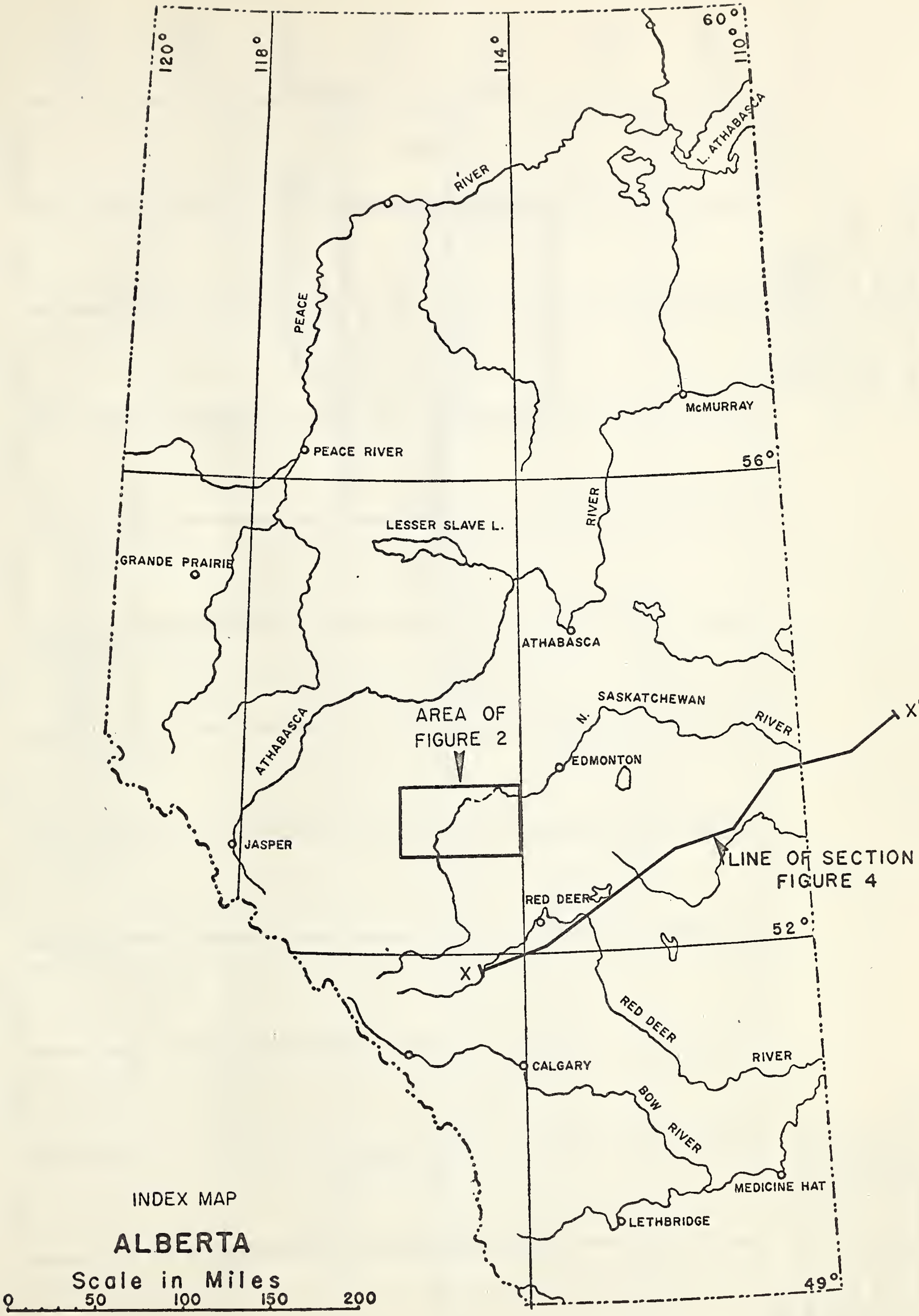
CHAPTER ONE - INTRODUCTION

GENERAL STATEMENT

This thesis is a subsurface study of the basal Belly River sandstone of Upper Cretaceous age in the Keystone area of the Pembina field which lies in the central plains of Alberta. The study covers Township 47, Ranges 2 and 3 and Township 48, Ranges 2, 3 and 4, west of the 5th Meridian, an area of 180 square miles (Figures 1 and 2).

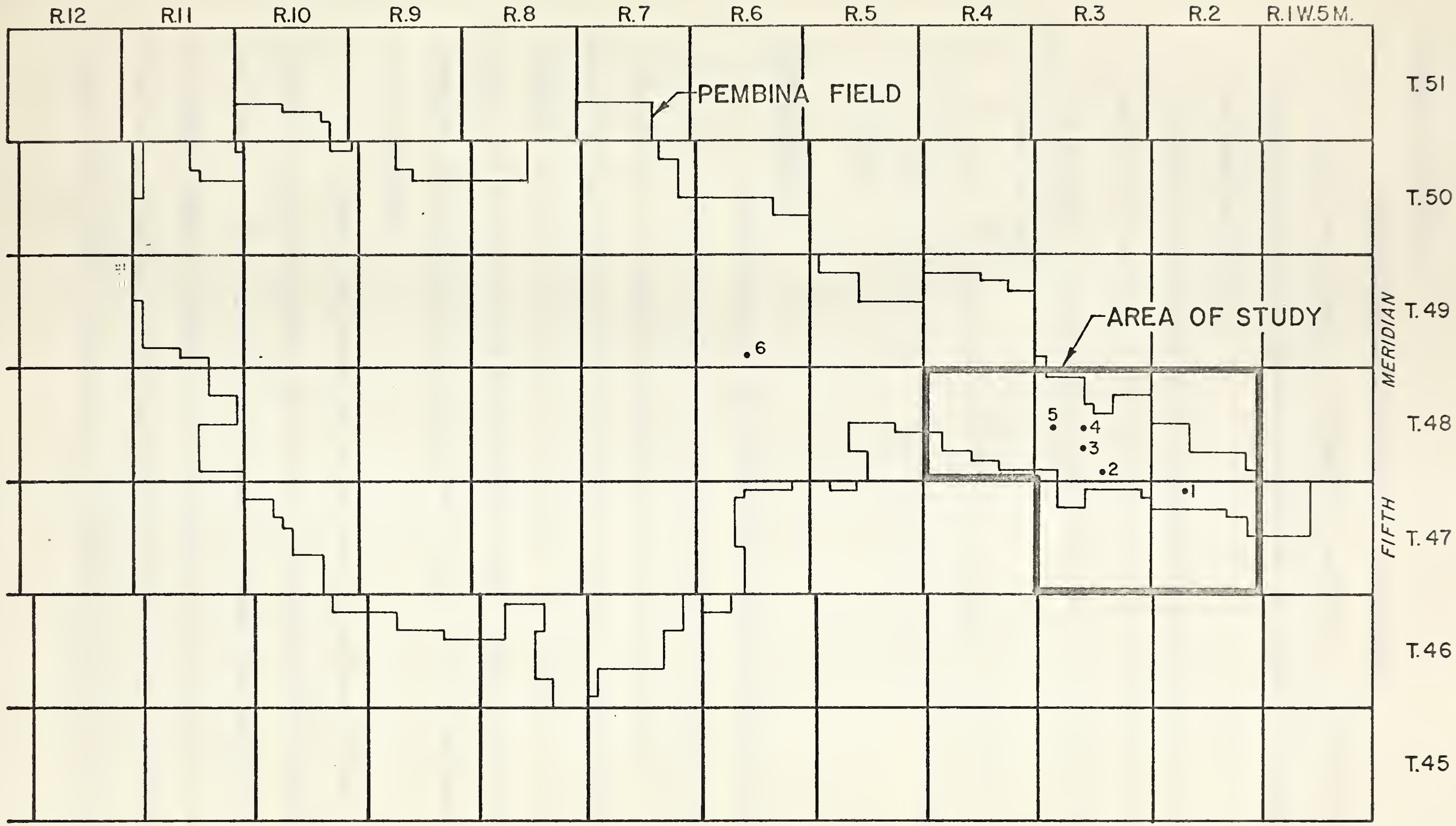
The area was selected for study because of the following reasons:

1. Abundant well control is available with a spacing of 160 acres over most of the area.
2. Oil and gas occurs in the basal Belly River sandstone in the area. A total of 15.5 million stock tank barrels of recoverable oil reserves has been estimated for the area, out of which approximately 1.3 million stock tank barrels of 37° API oil has been produced (data as of July 1, 1963, Oil and Gas Conservation Board, Calgary).
3. A total of 1550 feet was cored in the basal Belly River sandstone in about 35 of 200 wells drilled in the area studied. Core recoveries in most of the wells studied were complete.
4. About 50% of the wells were tested in the basal Belly River sandstone and the fluid recovery data were available.
5. No subsurface work on the basal Belly River sandstone has been published.



120°
118°
114°
110°
60°
56°
52°
49°
L. ATHABASCA
RIVER
PEACE
McMURRAY
PEACE RIVER
RIVER
LESSER SLAVE L.
GRANDE PRAIRIE
ATHABASCA
SASKATCHEWAN
N.
RIVER
AREA OF
FIGURE 2
ATHABASCA
EDMONTON
X'
LINE OF SECTION
FIGURE 4
JASPER
RED DEER
X
RED DEER
RIVER
CALGARY
BOW
RIVER
MEDICINE HAT
LETHBRIDGE
INDEX MAP
ALBERTA
Scale in Miles
0
50
100
150
200

FIGURE 1



WELLS

1 Whitehall Key. Pem. 8-31 (C,T)
2 Whitehall Key. 6-3 (C,P,X)
3 Whitehall Key. 14-9 (C,P,T,H,X)
4 CS War. Key. Pem. 14-16 (C)
5 CS War. Key. Pem. 16-18 (C)
6 Imp. Can. Sup. Berrymoor 8-4C (C,P,X)

WELL LEGEND

C Core description
P Particle size analysis
T Thin sections
H Heavy mineral sample
X X-ray diffraction samples

FIG. 2 PEMBINA OIL FIELD

PURPOSE OF THESIS

The purpose of this thesis is threefold:

1. To study the geometry, distribution pattern, and petrology of the basal Belly River sandstone bodies and to suggest a possible mode or modes of origin.
2. To study the behavior of the spontaneous potential in the basal Belly River sandstone and to attempt to relate variations in petrography to variations in the response of the spontaneous potential log.
3. To relate the geometry, distribution pattern, and petrology of the basal Belly River sandstone to the accumulation of hydrocarbons.

SCOPE OF WORK

Prospecting for lenticular sand bodies, understanding their environment of deposition and predicting their trends are problems that continually confront an exploration geologist. Recently Busch (1959) has stressed the importance of relating the geometry of sandstone bodies to erosional, depositional and structural history of the rock units of which they form a part. For these reasons, the present study emphasizes the geometry of the basal Belly River sandstone.

Cores from seven wells, and well logs from 200 wells were examined, and the behavior of fluids in the wells which were tested was studied. The correlation of sandstone beds from well to well was based largely on lithology as determined from well logs, and in this respect markers in the underlying marine Lea Park Shale proved very useful. After correlation was established between available

control points, isopach, isolith, ratio and variability maps and cross sections were used to determine the geometry of the sandstone bodies.

Various graphical, analytical and statistical methods were employed to construct the residual anomaly maps used to study the effect of paleotopography in localizing the sandstone build-ups.

An I.B.M. 1620 computer was used in carrying out the stratigraphic analysis.

METHOD OF STUDY AND MATERIAL USED

Throughout the area under study, subsurface geologic techniques were used in addition to those of sedimentology and sedimentary petrography and X-ray diffraction techniques.

Electric log correlations of six markers - the top of Colorado Group (First White Specks), Lea Park 2, bottom of basal Belly River sandstone, top of basal Belly River sandstone, bottom of Coal 2 and bottom of Coal 1 (Figure 3) - were first established by using a network of closed correlation loops. Subsequently all adjoining wells were tied into these loops, and the well depth to each marker was recorded.

For preparing the sand isolith map, instead of measuring sand thicknesses, shale intervals greater than 1 foot thick within the basal Belly River sandstone were recorded. Also recorded were the spontaneous potential against the sand in the bore hole, the type of mud used, and the resistivities of the mud, mud-cake and mud filtrate with their temperature of measurement. The spontaneous potential was picked against the thickest sandstone where it is best developed. Because such sandstones are seldom less than 1.5 feet thick, no correction for the thickness of the bed was used.

TYPICAL ELECTRICAL LOG

Cities Service Keystone 16-14

Lsd. 16, Sec. 14, Twp. 48, Rge. 4W5
Elev. 2767 ft. (K.B.)

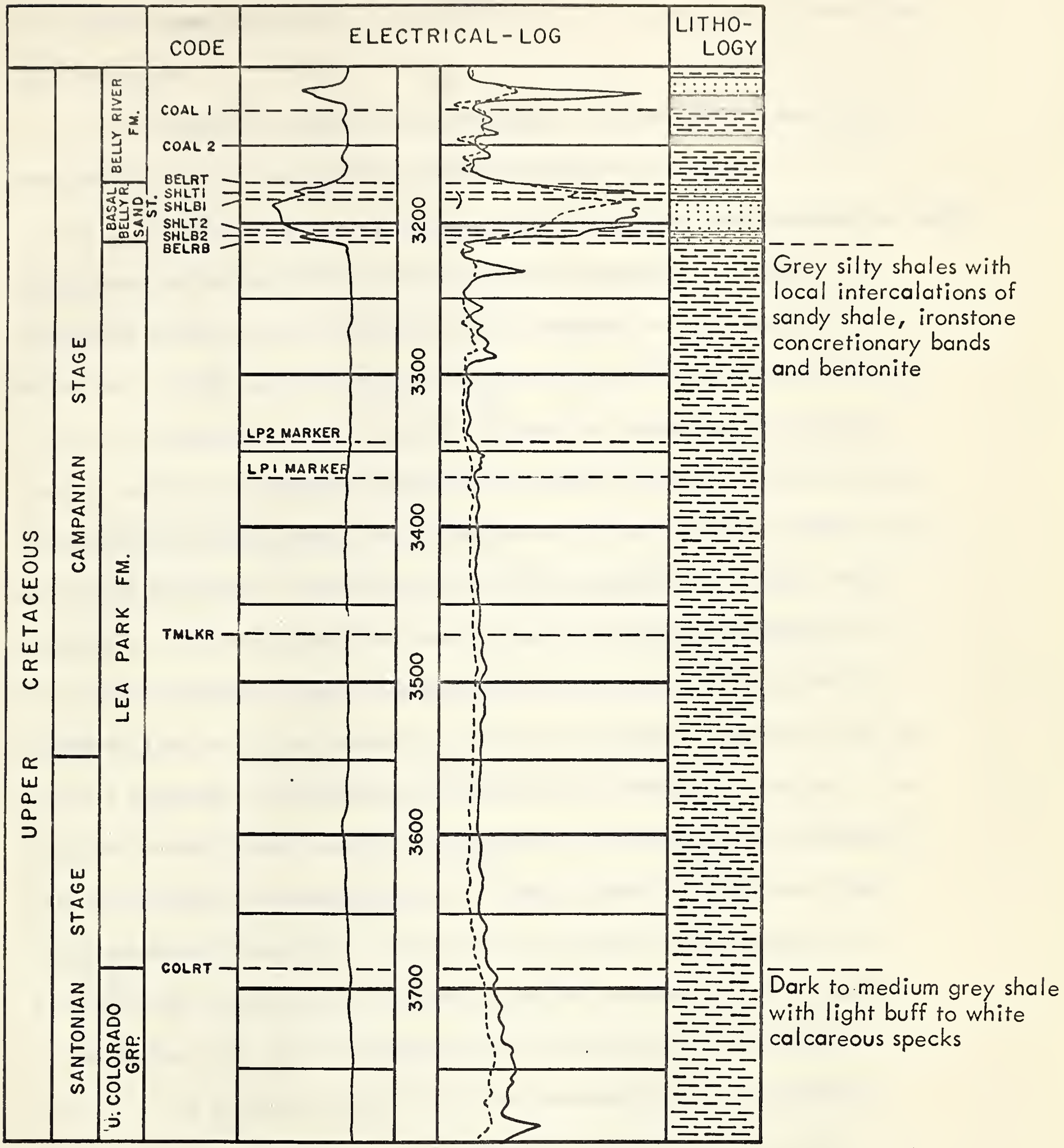
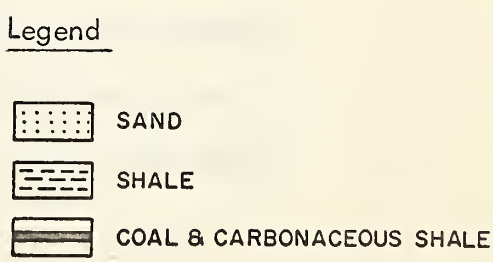


Fig. 3 Typical well in basal Belly River Sandstone showing stratigraphic nomenclature, codes to various markers, electrical log and lithology



Sandstone intervals between markers Coal 2 and Coal 1 and stray sandstone occurrences below the base of the Belly River sandstone were recorded.

Intervals tested while drilling, and production test intervals with the type of fluid recovered in each were noted.

The various data picked from the well logs were punched on cards and processed by an I.B.M. 1620 computer (Appendix K). About 20 different problems were answered by the computer in the form of a print out. These data formed the basis for the stratigraphic analysis.

Sandstones were identified from the spontaneous potential curve, and for the purpose of this study they were arbitrarily defined as those beds with a negative deflection of 10 millivolts or more from the shale base-line. All other beds were classified as shale. Where available, the micrologs were used to measure shale thicknesses up to 0.5 feet accurately. Spontaneous potential is poorly developed in wells drilled with low resistivity "calcium chloride - starch" mud; in fact, a reversal of spontaneous potential was sometimes observed. In such wells and in wells with no spontaneous potential log, sandstones were identified by interpretation of other types of mechanical logs (e.g. gamma ray - neutron; sonic). In some wells all logs are so poor that no interpretation of sandstone thicknesses could be made, although the logs may be satisfactory for purposes of correlation.

It should be noted that such determinations of sandstone thickness can not, however, be considered as precise for various reasons: firstly because the exact relationship between "permeable beds" as defined by spontaneous potential curve, and the actual petrography of the rocks, is not known; secondly, when thin shale

bands (0.5 to 2 feet) are sandwiched between thick sandstones, the spontaneous potential curve only responds by minor deflections or ripples which are difficult to pick and interpret, and further such minor deflections or ripples ignoring bore hole effects, may be due to calcite-cemented sandstone streaks within a porous non-calcareous sandstone; and thirdly, the response of the spontaneous potential log depends on the hole conditions at the time of logging (mainly mud character, hole size, depth of mud filtrate invasion into the bed, and temperature) and the formation fluid as well as the lithology of the strata penetrated.

The coal markers were easy to pick on electrical logs and sometimes on sonic logs. However, other types of logs do not respond well and the markers were not picked in the absence of these first noted logs. The thicknesses of the coal beds were not recorded as they were fairly consistent throughout the area under study and only the base of the respective coal beds were picked.

Megascopic description of cores from six wells was made using a binocular microscope (Appendix C). Terminology for stratification and cross-stratification was used as proposed by McKee et al. (1953). The criteria for describing the cement, shale content, etc. in sandstones are those used by Core Laboratories Canada Ltd., Calgary (Appendix B). The lithology was plotted and minor depth adjustments were made to match the lithology with electrical log features (Appendix E).

Samples were collected by slabbing the core every four feet and taking chips every 2 feet. Sampling intervals were adjusted depending upon lithological variations. These samples were used for

mechanical analyses, thin sections and heavy accessory minerals and X-ray diffraction studies.

Complete mechanical analyses on nine samples from three wells were made. Mechanical analyses on four samples were repeated to test the reproducibility of the results.

Eleven thin sections of sandstones were examined using a petrographic microscope. Grain counts on two of the sections were made to help in classifying the sandstones.

Heavy minerals were extracted from one sample by the use of tetrabromoethane (S.G. = 2.94 @ $20^{\circ}C$) and standard technique. The grains were mounted in "Aroclor" (n = 1.66) and counted to determine their relative abundance.

The identification of clay minerals was done on oriented slides using X-ray diffraction techniques.

The relative abundance of minerals present in the size fraction smaller than 4 phi (.0625 mm) was determined semi-quantitatively using peak height ratios on X-ray diffraction patterns from eleven samples.

Sample locations are given in Appendix A.

PREVIOUS WORK

No previous work has been published on the basal Belly River sandstone in the subsurface of the central Alberta plains.

Allan (1918) introduced the name Brosseau for the basal Belly River sandstones exposed along the North Saskatchewan River valley in the east-central Alberta plains. He described the beds as consisting of flaky and clayey sandstones in the upper part, and brown sandy shales, thin bedded sandstones and thin seams of coal in the

lower part. Shaw and Harding (1954) recognized the Brosseau beds in subsurface in east-central Alberta plains, delineated their extent and gave them a member status.

Slipper and Hunter (1931) named the basal unit of the Belly River Formation the Verdigris Sandstone in the southern Alberta plains. They observed the base of the sandstone to be transitional into the underlying Pakowki Shale whereas the upper contact was well defined. The Verdigris Sandstone was considered to be the beach sandstone facies of the retreating Montana sea.

Douglas (1951) observed the basal Belly River sandstone to be overlain by fissile dark grey shales and thin coal seams or carbonaceous shales in the Pincher Creek area in the southern Alberta plains.

Mellon (1961) worked on the equivalent section exposed in the foothills of the Crowsnest Pass region of southwestern Alberta. He considered the basal Belly River sandstone to have been deposited along the margin of a regressing late Cretaceous Colorado sea. Mellon described the basal Belly River sandstone as consisting of about 100 feet of typically pale grey, fine to medium grained, "salt and pepper", well sorted, cross bedded, calcareous sandstones which tend to split along certain bedding planes formed by the concentrations of thin layers of biotite. In the area where he worked, sedimentary magnetite deposits overlie the basal Belly River sandstone with sharp contact in contrast to the lower transitional contact with the underlying Wapiabi Shale.

USE OF COMPUTERS IN STRATIGRAPHIC ANALYSIS

The use of electronic computers in exploration is oriented

towards furnishing the geologist with an additional tool. It frees him from much busy work and gives him more time to interpret and use his final maps. The advent of computers has made possible a change in the entire framework of map preparation, analysis and interpretation by furnishing quicker ways of assembling, sorting and processing the basic data.

Data processing is often merely a system of recording the objective well history data in numerical form on cards or tape for computer input. The objective well data may consist of well locations, formation tops, rock types, thicknesses within stratigraphic intervals, drill-stem test data, depth and type of shows, core descriptions, types of logs and completion information or any other information which can suitably be expressed in numerical form. The number of cards and the cost for obtaining objective data on punched cards or tape depends on the completeness desired, the accuracy required, and the form and accessibility of the source documents. The general purpose of recording objective data is to have rapid access to data fulfilling specified requirements. From such input, the computer can calculate structure and isopach values, and various types of lithofacies, biofacies and environmental data for map preparation. These data can be obtained in a very short time in comparison to manual assembly. The results may either be printed rapidly on data sheets and then plotted manually on maps, or automatic plotting equipment may be used to print the output directly on base maps.

Map comparison and use of maps as predicting devices can be achieved rapidly by trend surface analysis. For a map containing for example, 200 data points, several weeks would be required to

perform a least squares power series analysis up to cubic terms on a desk calculator. The same calculations may be performed on a computer in a few minutes.

In regional geologic studies involving a comprehensive collection of information from hundreds or even thousands of wells, the collection of input data in itself can be a major effort on the part of a subsurface geologist. Converting large volumes of geological data to a form suitable for computer input can be done economically with proper planning by trained geologists. Expensive or elaborate equipment is not essential for obtaining the data to be punched on cards for computer input.

In the present study an average of about 27 different pieces of information was picked from each of 200 wells, resulting in a total of about 5,000 observations as input punched on about 600 cards.

CHAPTER TWO - STRATIGRAPHY

GENERAL STATEMENT

The Belly River Formation is of Upper Cretaceous age (Lower Campanian) in the central Alberta plains. It is dominantly a continental sequence about 1000 to 1500 feet thick and is composed mainly of lenticular, fine to medium grained sandstones interbedded with mudstones, shales and thin coals. It interfingers with marine shale in the eastern Alberta plains and becomes increasingly continental and thicker towards the west. The lower contact is transitional into the underlying marine Lea Park Shale and rises stratigraphically towards the east. It is conformably overlain by the Bearpaw Formation composed of dark grey marine shale which thins westerly and northwesterly so that in the Pembina oil field its thickness is 100 feet or less (Williams and Burk, in press). Further west, and northwest, the continental Edmonton Formation directly overlies the Belly River Formation.

Facies variation indicate that the clastics for the Belly River Formation were derived from a western source area.

UPPER COLORADO GROUP

The upper Colorado Group comprises the strata between the base of the Fish Scales Marker and the top of the First (Upper) White Specks in central and southern Alberta plains (Williams and Burk, in press). In the area under study, it consists of a relatively uniform thick section of dark to medium grey marine shale with minor sandstone, shaly limestone and bentonite horizons. The top 100 - 150 feet of shale contain small white calcareous specks with an average diameter

of 0.2 millimeter. The top of the upper Colorado Group is placed at the highest occurrence of the speckled shale.

LEA PARK FORMATION

The Lea Park Formation was named by Allan (1918) for a marine shale cropping out in the vicinity of Lea Park on the North Saskatchewan River.

The formation is a uniform sequence of grey, silty shales with local intercalations of sandy shale, limestone and ironstone concretionary bands containing bentonite and fossil molluscs. In the area under study, the formation varies in thickness from 450 to 500 feet (Figure 6).

Shaw and Harding (1954) in the eastern Alberta plains showed that the Lea Park Formation grades upward into the sandstones of the Belly River Formation. The marine shale tongues which interfinger with the deltaic sandstones of the Belly River being considered to be members of that formation. Accordingly, the contact has a "stair step" character, with increasing thickness of Lea Park marine shale to the east due to successive lensing out of the sandstone members of the Belly River Formation in that direction. Thus the upper limit of the Lea Park Formation occurs at higher stratigraphic levels towards the east because marine conditions lasted longer there.

BELLY RIVER FORMATION

The term Belly River was originated by Dawson (1883) for "...a series of pale, generally greyish and arenaceous beds at least two hundred feet in thickness...underlying the Pierre shales...on both the Bow and Belly rivers and elsewhere (pp. 7B and 8B)". The Pierre

EPOCH	STAGE	SOUTHWEST ALBERTA	SOUTHEAST ALBERTA SOUTHWEST SASKATCHEWAN	EAST CENTRAL ALBERTA (SHAW & HARDING) (1947)	SOUTHWEST MANITOBA	CENTRAL FOOTHILLS ALBERTA	NORTHWEST PLAINS
UPPER CRETACEOUS	?MAESTRICHTIAN	ST. MARY RIVER	BATTLE	EDMONTON	BOISSEVAIN	BRAZEAU	WAPITI
			WHITEMUD				
			EASTEND				
	CAMPANIAN	BLOOD RESERVE	BEARPAW	BEARPAW	RIDING MTN.		
		BEARPAW					
		BELLY RIVER: OLDMAN	BELLY RIVER: OLDMAN	OLDMAN MBR.			
				U. BIRCH LAKE MBR.			
				MULGA MBR.			
				L. BIRCH LAKE MBR.			
				GRIZZLY BEAR MBR.			
		BELLY RIVER: FOREMOST	BELLY RIVER: FOREMOST	RIBSTONE CREEK MBR.			
				VANESTI MBR.			
				VICTORIA MBR.			
				SHANDRO MBR.			
				BROSSEAU MBR.			
		PAKOWKI	PAKOWKI	LEA PARK	PEMBINA	WAPIABI	WAPIABI
	– LATE – SANTONIAN	MILK RIVER	MILK RIVER				

TABLE I BELLY RIVER AND CONTIGUOUS FORMATIONS IN WESTERN CANADA

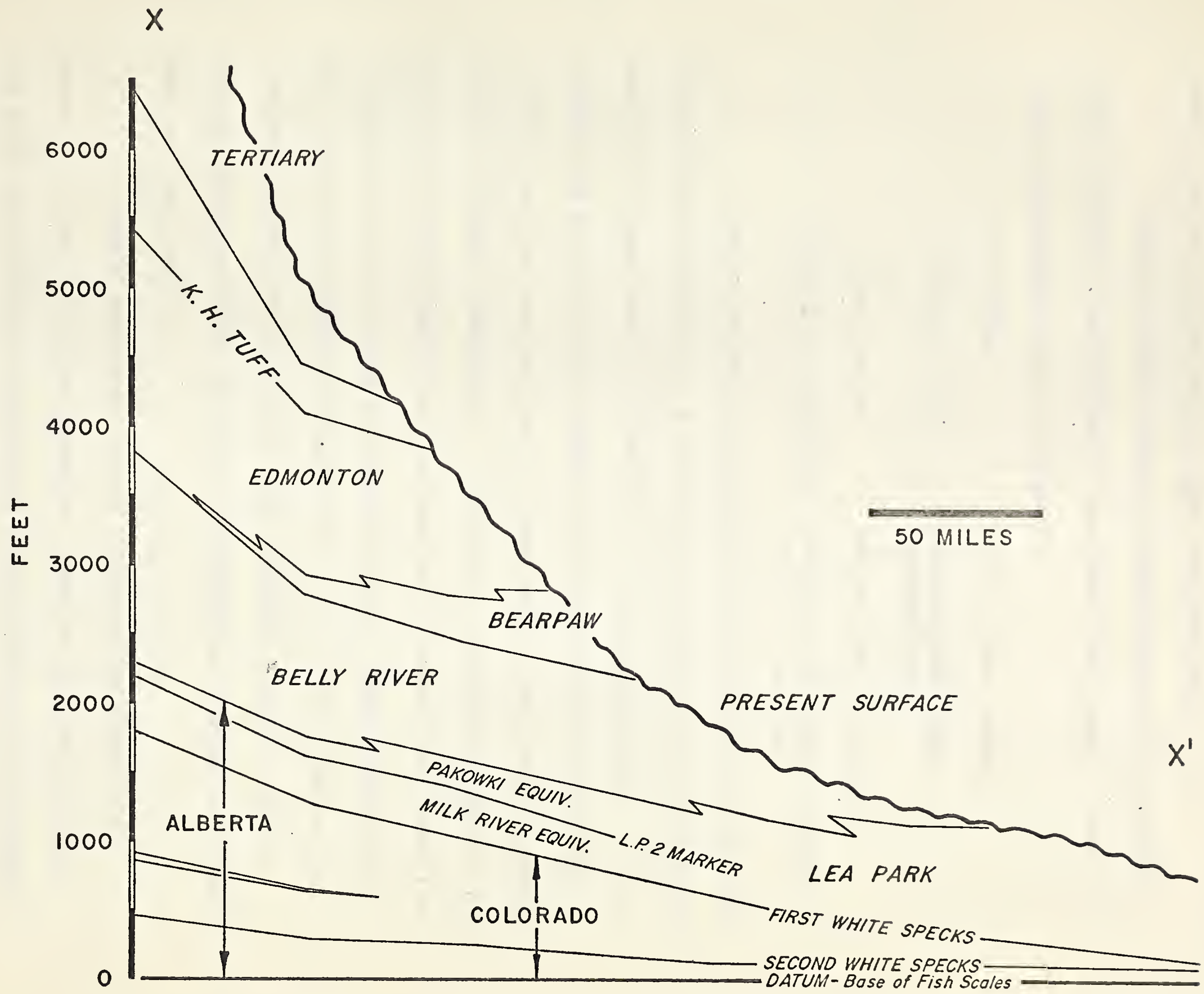


FIG. 4 STRAT. CROSS SECTION X-X', UPPER CRETACEOUS ALBERTA AND SASKATCHEWAN

After Williams & Burk, in press

Shale is partly equivalent to the Bearpaw Formation.

Tyrrell (1887) used the name Belly River for the sandy beds underlying the Bearpaw Shale in the Vermilion area.

Dowling (1914) studied the Belly River of the southern plains of Alberta and divided it into four stratigraphic units, as shown in descending order as follows:

Pale Beds	(mainly fresh water)
Foremost Beds	(yellow banded beds, brackish water)
Pakowki Shales	(mainly shales, marine)
Milk River Sandstone	(mainly fresh water, brackish water at the top)

Dowling pointed out that the lower part of the Milk River Formation was deposited in a regressive Colorado sea, the middle and most of the upper part of the Milk River being continental. He considered the Foremost Beds to have been deposited in a fluctuating, slowly regressive sea and the Pale Beds above to have been deposited under continental conditions. To the east, equivalent sediments contain less coarse material and are more argillaceous, from which fact he deduced that the source area was the newly elevated land in the west. Due to the absence of subsurface data at that time, he did not know how far east the Belly River extended under the plains. Dowling recognized that the Milk River Sandstone pinches out towards the north and east.

Russell and Landes (1940) supported Dowling's interpretation of the Milk River Sandstone pinch-out towards the east and north and considered part of the Lea Park Formation of central Alberta to be equivalent to the Milk River.

A detailed study of the basal member of the Foremost Formation above the marine Pakowki Shale in southern Alberta showed that it grades into marine beds eastwards (Russell, 1939).

The Belly River sequence has been assigned to various ranks from time to time. It is considered to be a group in the type area where it consists of Russell's Foremost and Oldman Formations. Shaw and Harding (1954) felt that Russell's Foremost and Oldman subdivisions could not be maintained in east-central Alberta, and used the term Belly River as a formation name, dividing it further into various members.

The Belly River is variously defined as to stratigraphic interval. Dawson (1883) originally applied the name Belly River to the interval between the top of the Colorado Shale and the bottom of the Bearpaw Shale but his failure to recognize the correct stratigraphic position of the "Pakowki" shale introduced uncertainty as to how much section his term should embrace (Lerbekmo, 1961). Dawson perhaps mistook the Pakowki for the Colorado. Dowling (1914, p. 33) defined the Belly River to include the whole interval between the top of the Colorado shale and the bottom of the Bearpaw shale. Williams and Dyer (1930, p. 16) redefined the Belly River Formation in accordance with what they believed was Dawson's original intent, to include only the units above the Pakowki Shale. This latter usage has been generally accepted by petroleum geologists working on the plains.

The undivided Belly River Formation consists of a series of grey, brownish grey and greenish grey, argillaceous, bentonitic sandstones closely interbedded with brownish grey to grey,

carbonaceous shales and siltstones. Thin carbonaceous layers are characteristic of the normal facies, and thin coal seams characterize the continental to marine transition facies.

The Belly River beds appear to have been deposited as a complex of flood plains and deltas between the highlands on the west and epicontinental seas on the east.

The thickness of the Belly River Formation varies between 1100 and 1300 feet in the Pembina field area (Williams and Burk, in press).

Basal Belly River Sandstone

The basal Belly River sandstone varies in thickness from 10 to 60 feet in the area under study and is composed of medium to light grey, fine to medium grained, "salt and pepper", moderately sorted, occasionally calcareous sandstones with low angle cross-beds and cross-laminae. It is underlain by marine Lea Park Shale and is overlain by coal beds either directly or with a varying thickness of shale interval between. Such a succession may represent a cycle of deposition starting from marine shale at the base, through beach sandstone to continental (lagoonal) coal beds at the top, deposited along the shoreline of the Lea Park sea.

The contact of the basal Belly River sandstone with the underlying Lea Park Shale is mostly gradational and a transition interval comprising shaly sandstones and sandstone streaks in shale may be present. This is reflected by an interval of low spontaneous potential response, usually less than -10 millivolts beneath the lowest sandstone, observed in most of the wells in the area under study. The vertical gradation downward from sandstone through shaly

sandstone and sandstone streaks to shale suggests a progressive shallowing or regression of the sea giving rise to what is called a progradational sequence. Further, markers in the Lea Park Shale immediately below the basal Belly River sandstone, when traced westwards are replaced, in turn, by sandstones beginning with the top marker. In other words, the bottom of basal Belly River sandstone drops stratigraphically towards the west. These features make the bottom of the basal Belly River sandstone an unreliable time-stratigraphic marker.

Markers in the Lea Park Shale were of great help in understanding the geometry of the sandstone bodies, their nature of contact with the underlying shale and mode of origin. Once good correlation was established through the Lea Park Shale, tracing the bottom of the basal Belly River sandstone became relatively easy.

The top of the basal Belly River sandstone is usually in sharp contact with the overlying shale. However, when a rapid pinch and swell of the sandstone occurs, as when going from one sandstone body to another, the top may be less easily determined because of the disappearance of some sandstone beds and the appearance of others. In such cases, the top of the highest occurring sandstone with spontaneous potential greater than -10 millivolts and lying below the lowest coal bed was taken as the top of the basal Belly River sandstone. Occasionally when the sandstone is thick, the intervening shale between the sandstone and the coal is absent and the coal may lie directly on the sandstone. In other instances the sandstone may thicken and replace the lowest coal bed, or the coal may be sandwiched between sandstone beds and may not be shown by the electrical log.

Where the basal Belly River sandstone pinches out, the coal beds lie directly on the Lea Park Shale. Care must be exercised in these instances so as not to mistake a higher sandstone for the basal Belly River sandstone. Correlation of the sandstones is further facilitated by excellent markers in the underlying Lea Park Shale.

STRATIGRAPHIC ANALYSIS

Markers Used

Top Colorado/First White Specks Marker

The top of the Colorado Group provides the best log marker throughout the area. It may be picked from electrical logs, micrologs, induction electrical logs, laterologs, and radiation logs.

On resistivity-type logs, the marker is characterized by a small but sharp rise in the resistivity compared to more or less uniform and slightly lower resistivity of the overlying Lea Park Shale (Figure 3). Gamma ray logs, show higher intensity as compared to the Lea Park due to its higher radioactive content. The response on neutron logs is mostly poor. The top of the Colorado Group is considered to be a time marker in the area under study.

Lea Park Markers

L. P. 1 Marker: This marker is characterized by a small shift of the resistivity curves of electrical logs, induction electrical logs, laterologs and may be discerned on gamma ray logs. It can be traced throughout the area under study (Figure 3).

L. P. 2 Marker: This is the highest persistent marker in the Lea Park which can be traced throughout the Pembina field and is characterized by a small 'bump' on resistivity-type

logs and by an increase in the gamma ray intensity. This marker is equivalent to the top of the Milk River Formation of the southern plains. It persists over long distances in the central plains even though the sandstone is minor or absent (Workman, 1954). It is also considered to be a time marker in the area of study.

Basal Belly River Sandstone Markers

The basal contact is transitional with the underlying marine shale. In such cases, the base of the sandstone is taken at a point where the spontaneous potential curve reads -10 millivolts or more from the shale base-line. In wells where the spontaneous potential is not well developed, the base is taken at a point where the resistivity on the normal or lateral curves increases abruptly from the low resistivity of the underlying shale; or where the gamma ray log shows a fairly sharp negative response compared to the shale.

The top of the basal Belly River sandstone is often in sharp contact with the overlying shale or coal bed. Whenever the contact is transitional the same criteria as applied to determining the base is used to pick the top. Correlation lines on the bottom and top of the basal Belly River sandstone are oblique to the time lines in the shale section below.

Coal Markers

Coal beds are present above the basal Belly River sandstone in the area under study. Presence of coal beds was confirmed by the examination of cores with full recoveries. Two of these bottom coal beds were designated as Coal 2 and Coal 1 in ascending order. Electrically these are thin, highly resistive beds

surrounded by shales of low resistivities. The short (16 inches) normal usually shows high resistivities against these coal beds, the long (64 inches) normal curve reverses giving a "crater effect" and the lateral responds faithfully showing high resistivities (Figure 3). Coals are characterized by low velocities on sonic logs. It is difficult to pick them on induction-electrical logs, laterologs, and radioactivity logs.

For consistency in mapping, the markers Coal 2 and Coal 1 were taken at the base of the respective coal beds.

Coal 2 Marker: This marker is remarkably continuous throughout the area under study and can be traced with fair amount of confidence wherever electrical logs or sonic logs were available. It lies either directly on the basal Belly River sandstone or separated from it by an intervening shale bed up to 30 feet thick.

Coal 1 Marker: This marker lies above the Coal 2 marker with a varying interval of shale, shaly sand or sand. It seems to have the same lateral continuity as the Coal 2 marker.

Attempts made to pick markers a little above the Coal 1 marker were not encouraging, due to rapid lensing of sands. This perhaps suggests a continental, possibly fluviatile, origin for this part of the section.

The different markers picked, the nature of their response to various well logs and their quality as correlation tools are given in Table II.

Discussion of Maps

Structure Contour Maps

Figure 5 is a structure contour map on the top of the Lea

RESPONSE TO VARIOUS WELL LOGS

Name of Marker	Code	S.P.	Resistivity Normal	Resistivity Lateral	Induction	Laterolog	Sonic Log	Gamma Log	Neutron Log	Quality of Correlation
Bottom of Coal 1	COAL 1	Poor	Good	Good	Mod. to poor	Poor	Good	Poor	Poor	Good to Poor
Bottom of Coal 2	COAL 2	Poor	Good	Good	Mod. to poor	Poor	Good	Poor	Poor	Good to Poor
Top of Basal Belly River sandstone	BELRT	Good	Good	-	Good	Good	Good	Good	Good	Good
Bottom of Basal Belly River sandstone	BELRB	Good to mod.	Good to mod.	Good to mod.	Good to mod.	Good to mod.	Good to mod.	Good to mod.	Good to mod.	Good to mod.
LP2 Marker	-	-	Good	Poor	Good	Good	-	Good	Mod.	Good
LP1 Marker	-	-	Good to mod.	Poor	Good to mod.	Good to mod.	-	Good to mod.	Mod.	Good to mod.
-	TMLKR	-	Mod. to good	-	Mod. to good	Mod.	-	Mod.	Mod.	Mod. to Good
Top of Colorado	COLRT	-	Good	Mod.	Good	Good	-	Good	Good	Good

TABLE II

Park Shale. The elevations on which the contours are drawn were obtained by subtracting the well depth to the top of the Lea Park Shale from the elevation of the Kelly Bushing of the well.

The strike of the beds is northwest over most of the area. A regional homoclinal dip of about 25 to 30 feet per mile due southwest is observed. Although there is no closure in the area, anomalies are present.

The sand isolith overlay of the basal Belly River sandstone (Figure 5) shows no obvious relationship between topography on the Lea Park Shale and sandstone accumulations.

An attempt was also made to reconstruct the post Lea Park depositional surface by isopaching the interval from the top of the Colorado Group (First White Specks) to the top of the Lea Park Shale (Figure 6). Overlaying sand isoliths on this map again does not seem to indicate any relationship between topography on the Lea Park Shale and sandstone build-ups.

Figure 7 is a structure contour map on the top of the basal Belly River sandstone. The elevations on which contours are drawn were obtained by subtracting the well depth to the top of basal Belly River sandstone from the elevation of the Kelly Bushing of the well.

The beds strike northwest over most of the area. Although a regional homoclinal dip of 25 to 30 feet per mile due southwest is discernible, numerous local anomalies are present. Small vertical closures are present in two of the anomalies in the area under study.

A comparison of this map with the isopach and isolith maps of basal Belly River sandstone (Figures 8 and 9) shows that most anomalies conform to the outline of sandstone bodies and that

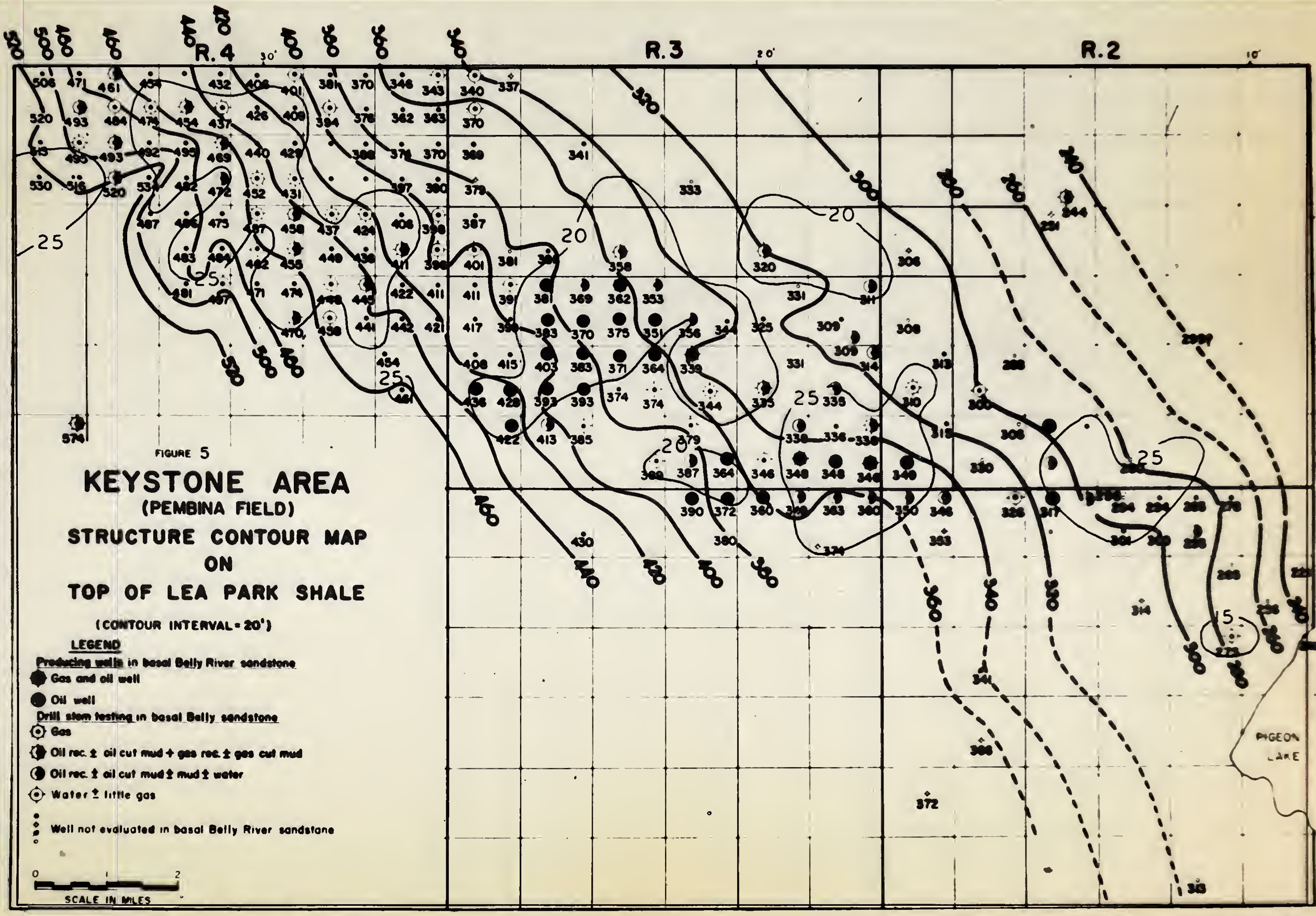


FIGURE An overlay of sand isoliths (See FIGURE 9)

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1969

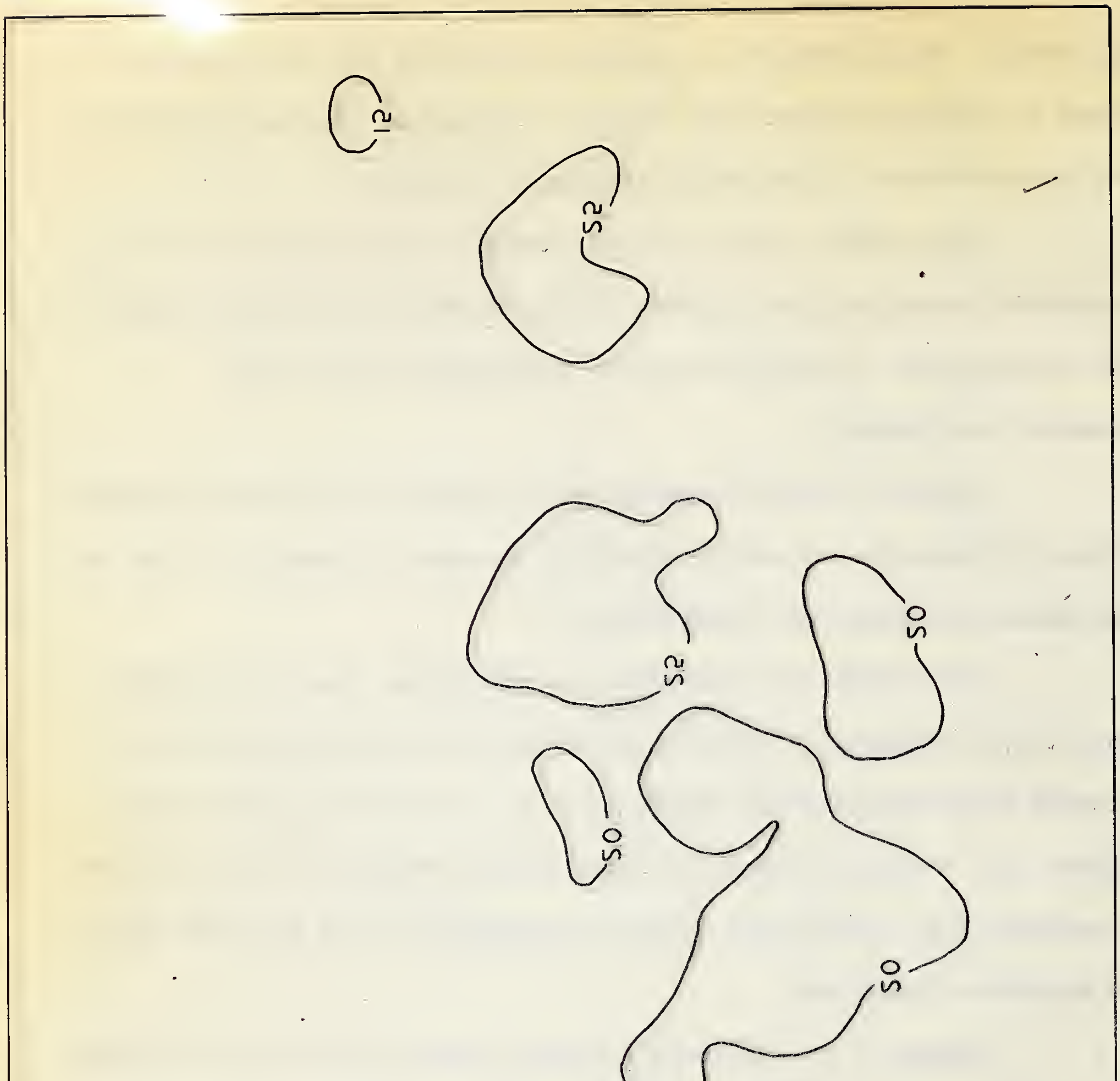


FIGURE An overlay of sand isoliths (See FIGURE 6)

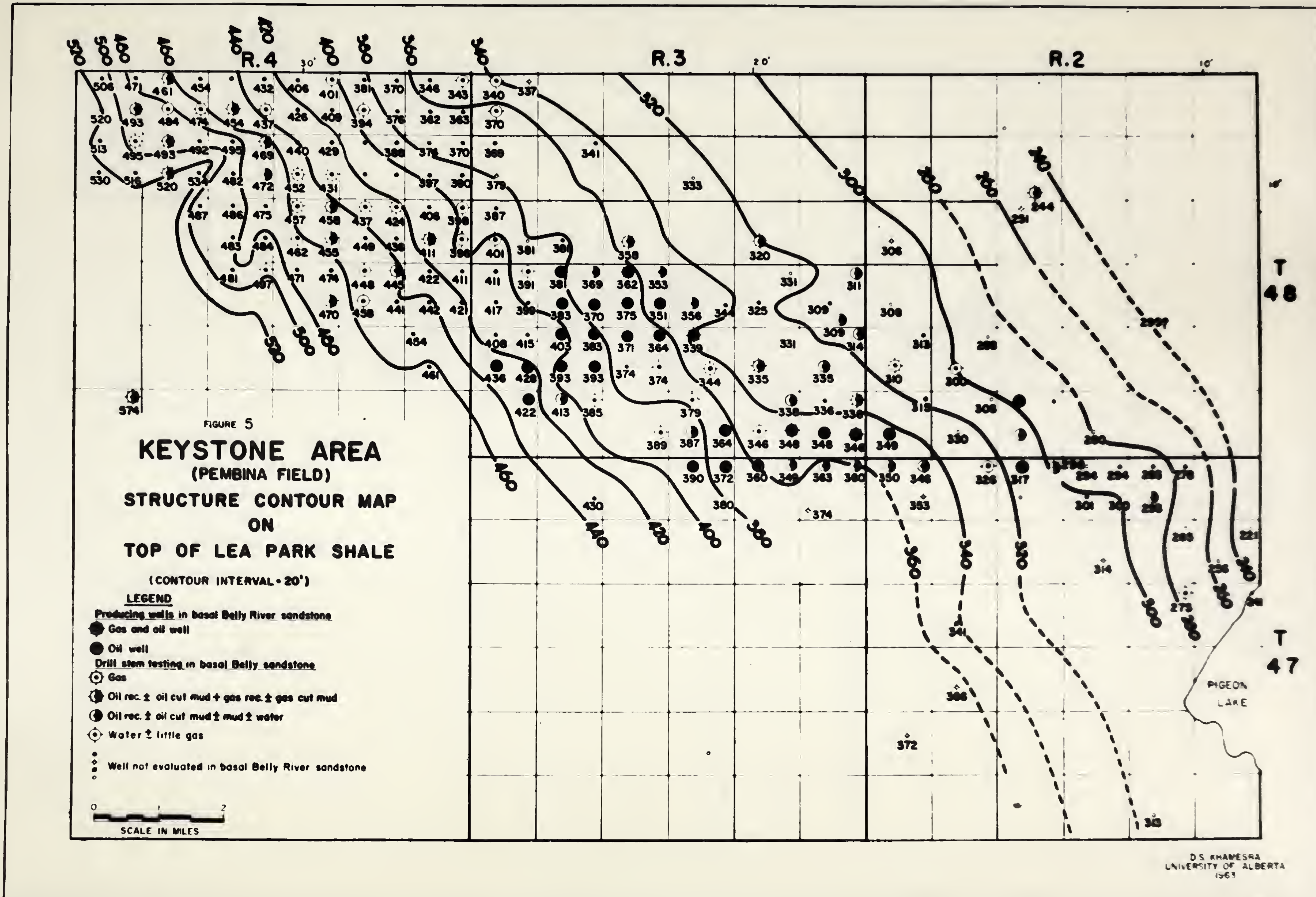


FIGURE 5

KEYSTONE AREA

(PEMBINA FIELD)

STRUCTURE CONTOUR MAP ON TOP OF LEA PARK SHALE

(CONTOUR INTERVAL - 20')

LEGEND

Producing wells in basal Belly River sandstone
- Gas and oil well
- Oil well

Drill stem testing in basal Belly sandstone
- Gas
- Oil rec. ± oil cut mud + gas rec. ± gas cut mud
- Oil rec. ± oil cut mud ± mud ± water
- Water ± little gas

Well not evaluated in basal Belly River sandstone

SCALE IN MILES

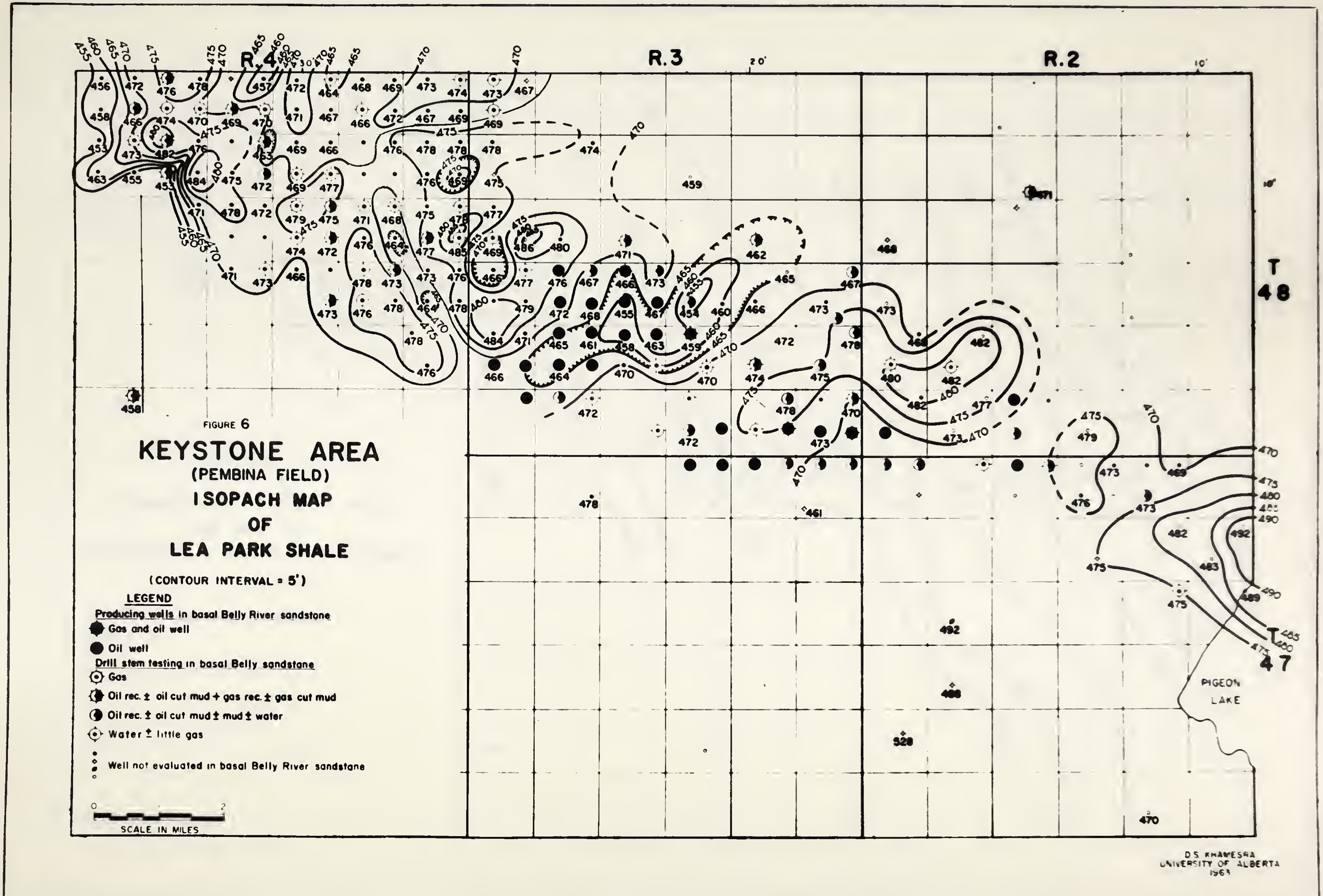
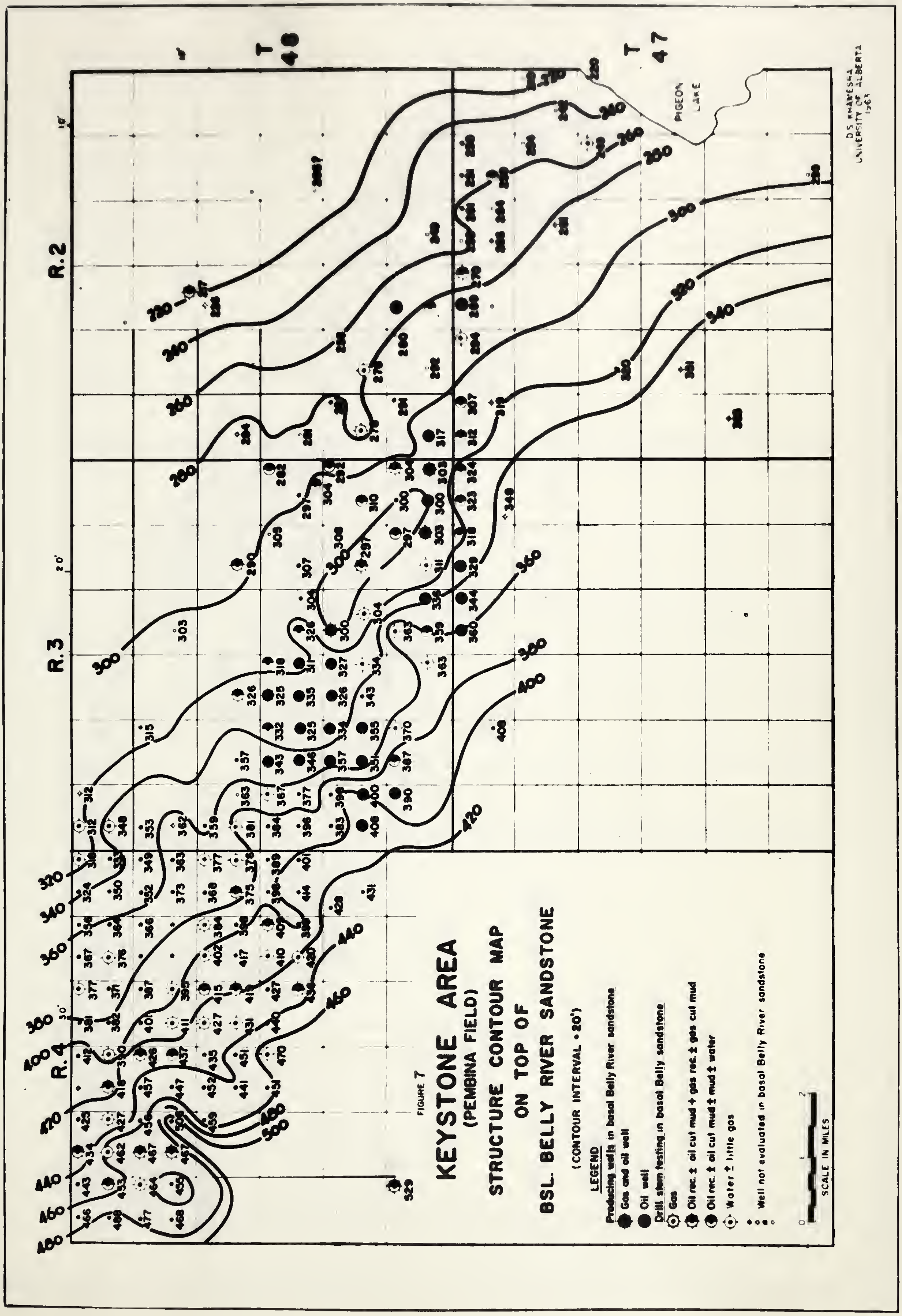
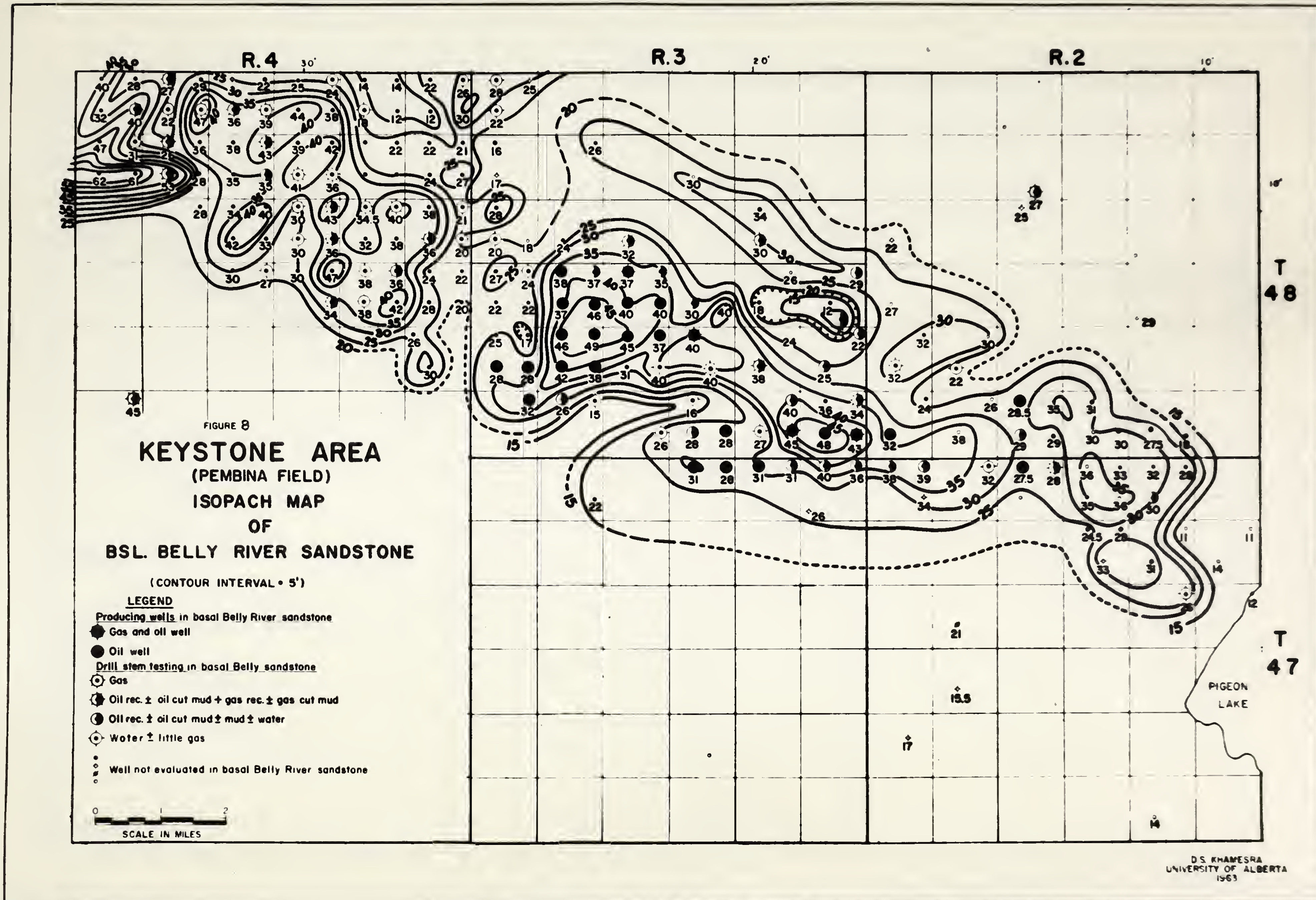


FIGURE 6
KEYSTONE AREA
(PEMBINA FIELD)
ISOPACH MAP
OF
LEA PARK SHALE
(CONTOUR INTERVAL = 5')
LEGEND
Producing wells in basal Belly River sandstone
Gas and oil well
Oil well
Drill stem testing in basal Belly sandstone
Gas
Oil rec. ± oil cut mud + gas rec. ± gas cut mud
Oil rec. ± oil cut mud ± mud ± water
Water ± little gas
Well not evaluated in basal Belly River sandstone
0
2
SCALE IN MILES
R.4
R.3
R.2
20'
10'
T 48
T 47
PIGEON LAKE
D.S. KHAMESRA
UNIVERSITY OF ALBERTA
1963


R. 2
R. 3
R. 4
T 48
T 47
PIGEON LAKE
UNIVERSITY OF ALBERTA
FIGURE 7
KEYSTONE AREA
(PEMBINA FIELD)
STRUCTURE CONTOUR MAP
ON TOP OF
BSL. BELLY RIVER SANDSTONE
(CONTOUR INTERVAL - 20')
LEGEND
Producing wells in basal Belly River sandstone
Gas and oil well
Oil well
Drill stem testing in basal Belly sandstone
Gas
Oil rec. ± oil cut mud + gas rec. ± gas cut mud
Oil rec. ± oil cut mud ± mud ± water
Water ± little gas
Well not evaluated in basal Belly River sandstone
SCALE IN MILES


R.4
R.3
R.2
30'
20'
10'
T 48
T 47
PIGEON LAKE
FIGURE 8
KEYSTONE AREA
(PEMBINA FIELD)
ISOPACH MAP
OF
BSL. BELLY RIVER SANDSTONE
(CONTOUR INTERVAL • 5')
LEGEND
Producing wells in basal Belly River sandstone
Gas and oil well
Oil well
Drill stem testing in basal Belly sandstone
Gas
Oil rec. ± oil cut mud + gas rec. ± gas cut mud
Oil rec. ± oil cut mud ± mud ± water
Water ± little gas
Well not evaluated in basal Belly River sandstone
0 1 2
SCALE IN MILES
D.S. KHAMESRA
UNIVERSITY OF ALBERTA
1963

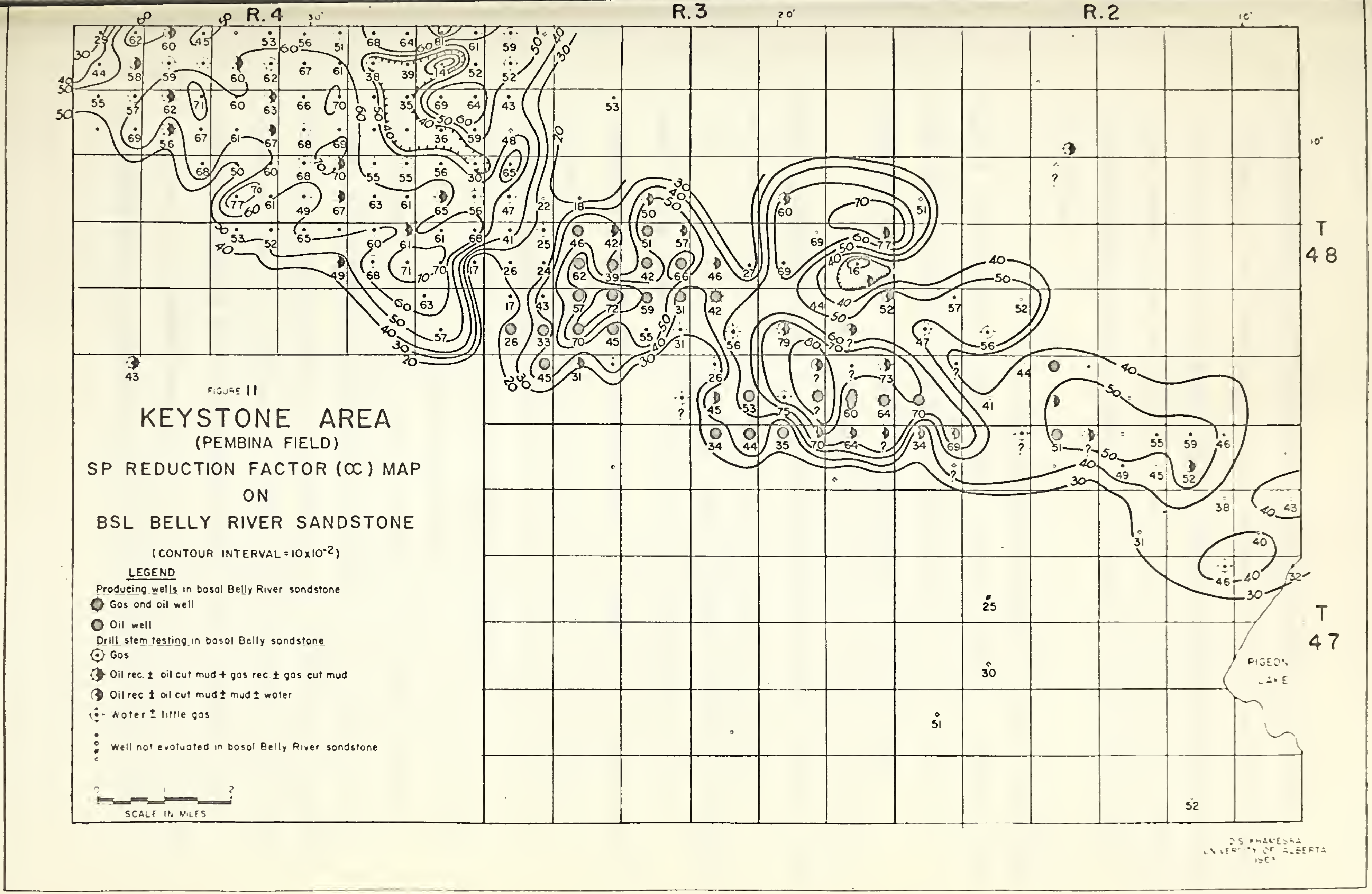


FIGURE 11

KEYSTONE AREA
(PEMBINA FIELD)
SP REDUCTION FACTOR (α) MAP
ON
BSL BELLY RIVER SANDSTONE
(CONTOUR INTERVAL = 10×10^{-2})

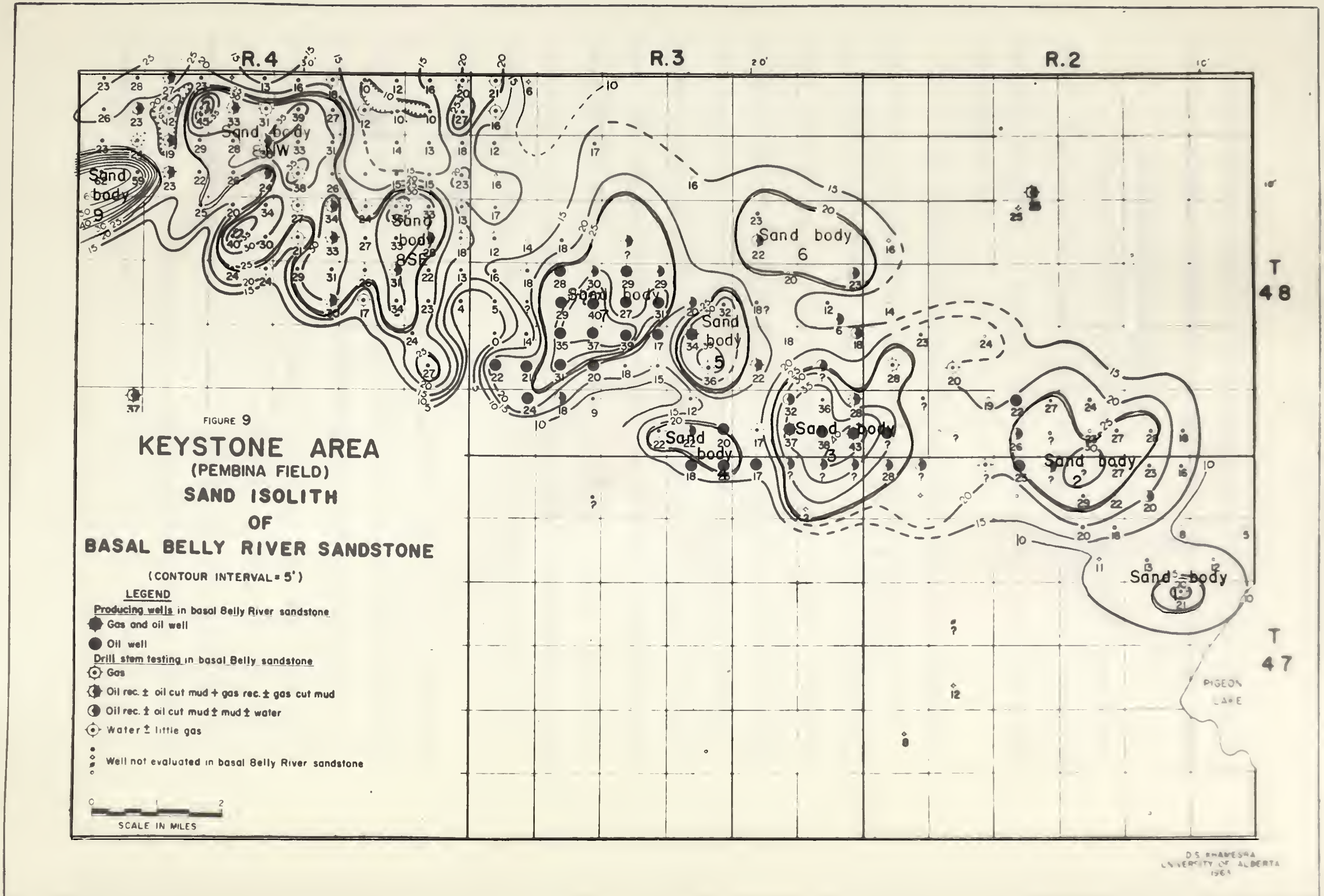
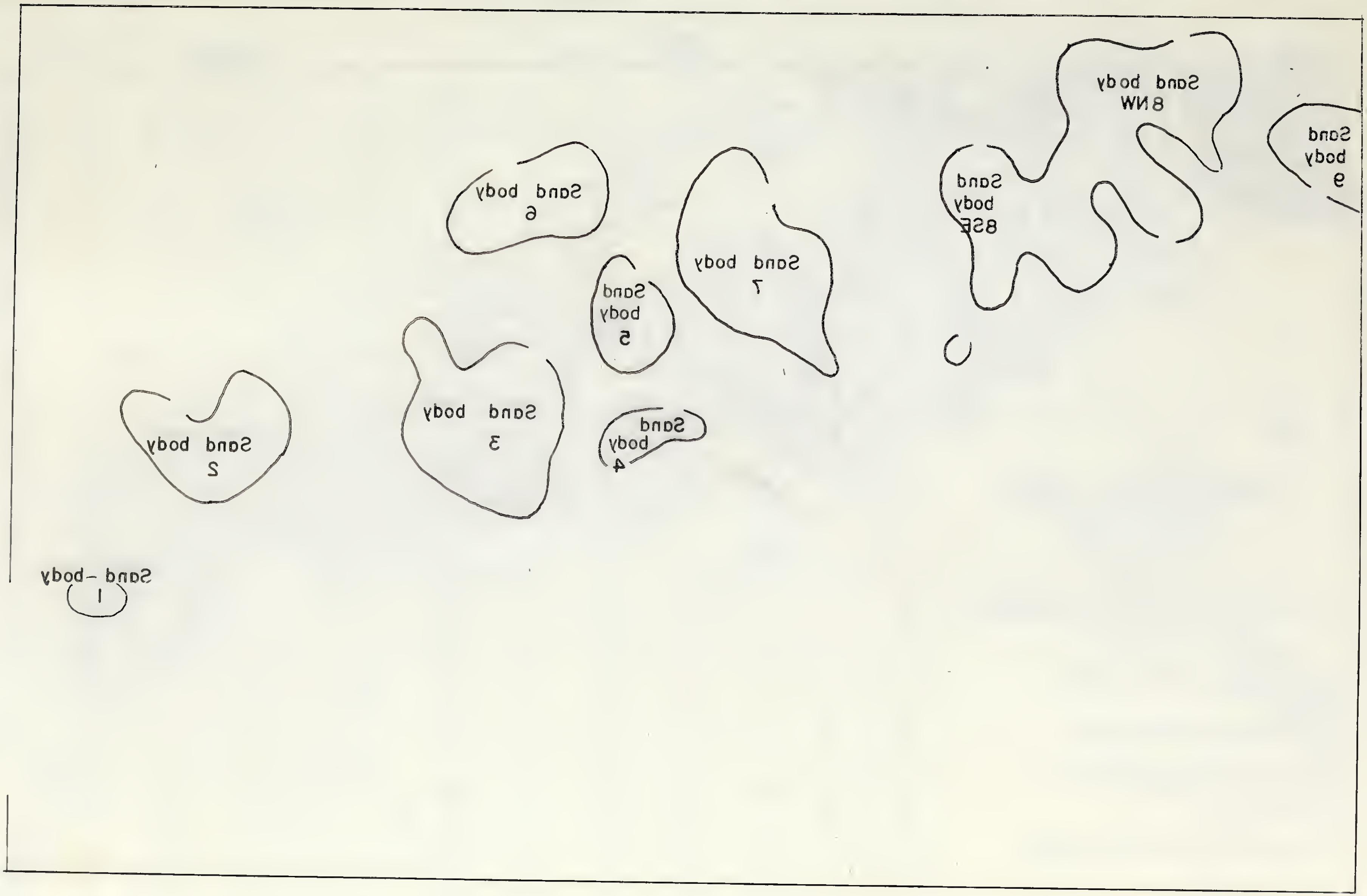


FIGURE 9
KEYSTONE AREA
(PEMBINA FIELD)
SAND ISOLITH
OF
BASAL BELLY RIVER SANDSTONE
(CONTOUR INTERVAL = 5')


Sand-body 1
Sand body 2
Sand body 3
Sand body 4
Sand body 5
Sand body 6
Sand body 7
Sand body 8SE
Sand body 8NW
Sand body 9

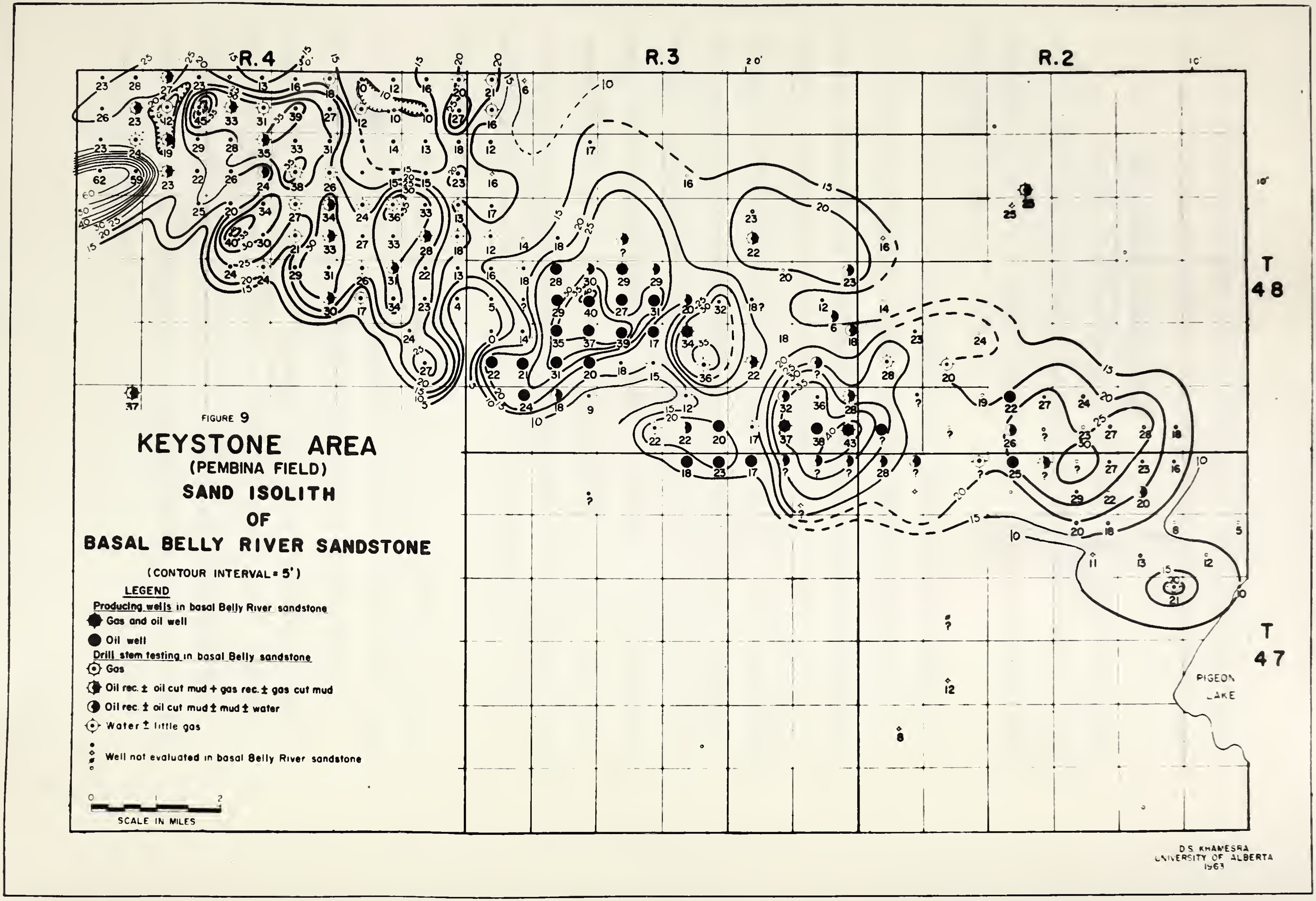


FIGURE 9
KEYSTONE AREA
(PEMBINA FIELD)
SAND ISOLITH
OF
BASAL BELLY RIVER SANDSTONE

structurally higher areas are underlain by thicker sandstones implying that the upper surfaces of the sandstone bodies are convex upward.

Isopach and Isolith Maps

Figure 8 is an isopach map of the basal Belly River sandstone. The sandstone pinches and swells in all directions and is thus irregular in habit. A general southeasterly thinning is evident from the values on the map.

An isolith map of basal Belly River sandstone (Figure 9) also shows an irregular pattern, but with greater variability and sharper features. From a regional view point, the lobe of sandstone seems to trend approximately northwesterly with decreasing values of isopachs towards the southeast. However, smaller local trends within this lobe seem to have their long axes striking north or northeast and are separated from each other by areas of poor sandstone development. The isolith values vary from about 60 feet in the northwest to about 20 feet in the southeast of the area under study. Though the sandstone is seldom entirely absent, at least 9 local sandstone bodies, marked and delineated on the overlay, can be observed in the area (Figure 9 overlay).

A relationship seems to exist between sandstone thickness and the accumulation of hydrocarbons. In the area under study, most of the productive wells and wells with indicated production lie within a 20 foot isolith in Townships 47 and 48 and Ranges 2 and 3 and within a 25 foot isolith in Township 48 and Range 4. This may suggest that dry wells result from either insufficient sandstone thicknesses or low permeability on the peripheries of the individual sandstone bodies or both.

Ratio and Variability Maps

The sandstone-shale ratio map shows the ratio of the aggregate thickness of sandstone to total thickness of shale in the mapped interval (Figure 10).

A section composed of half sandstone and half shale has a sandstone-shale ratio of unity. With increasing proportions of sandstone the ratio rises towards infinity and with increasing proportion of shale, the ratio drops towards zero.

Hubbert (see Krumbein & Sloss, 1951) suggested that a logarithmic contour interval be used on ratio maps, inasmuch as the rapid rate of decrease towards the lower ratio is somewhat misleading if a constant arithmetical interval is used. This suggestion was followed in this work. Coarse clastics normally characterize areas of turbulent nearshore deposition and fine muds those of quiet or deep water environment. The proportion of sandstone is thus an aid in determining depositional environments.

The sandstone-shale ratio map agrees closely with the isopach and sand isolith maps, and the isopachs and facies contours have similar trends.

The sandstone-shale ratio contour of 2 delineates the sandstone bodies and may thus serve as a boundary between two environments. A ratio lower than this may indicate relatively deeper and quieter water where mostly the mud was accumulated and a higher ratio may indicate areas where sands dominated over mud. These sandstone bodies surrounded by shale are ideal reservoirs for the accumulation of hydrocarbons.

Complementing the sandstone isolith map, the sandstone-

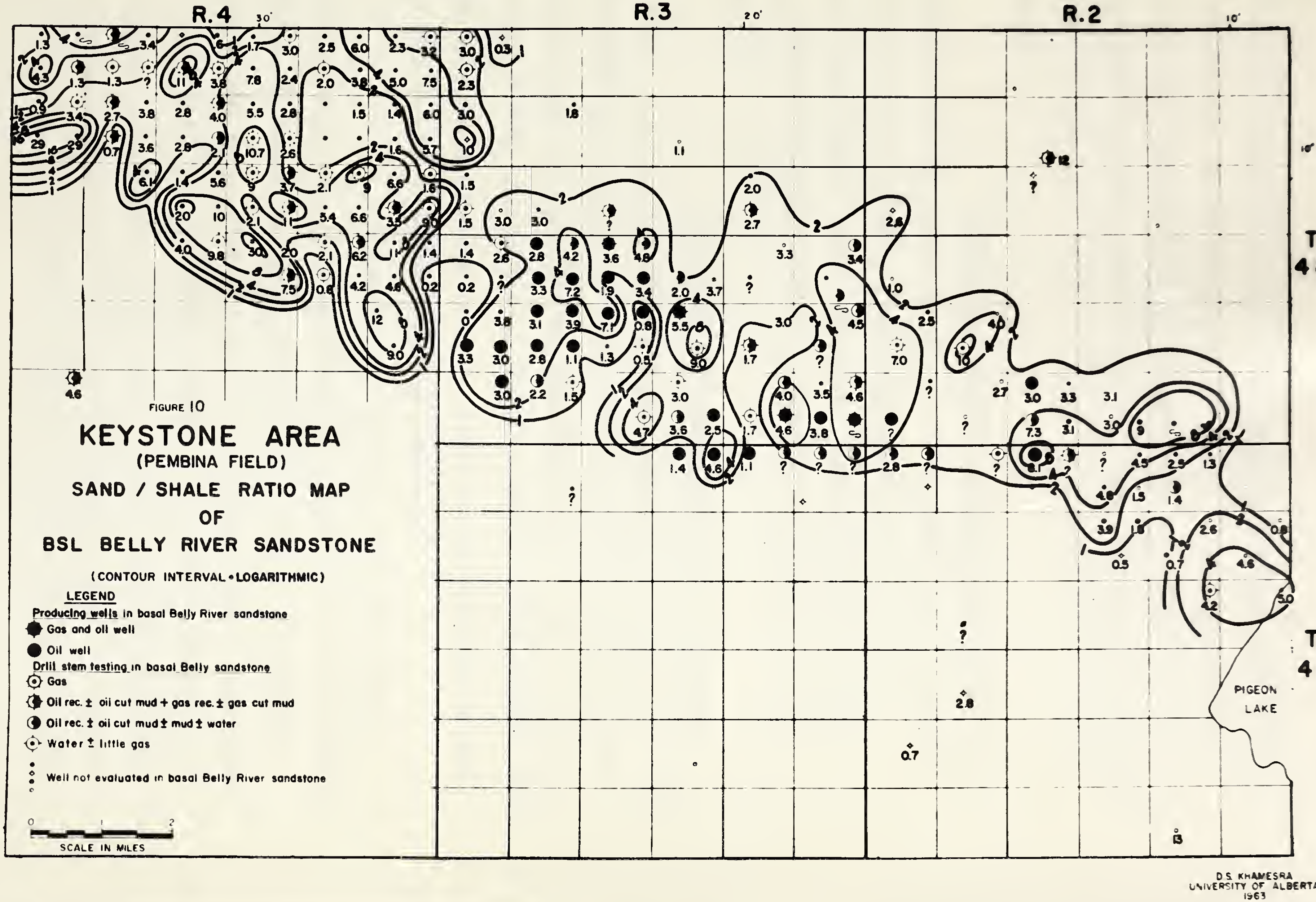


FIGURE 10

KEYSTONE AREA
(PEMBINA FIELD)
SAND / SHALE RATIO MAP
OF
BSL BELLY RIVER SANDSTONE
(CONTOUR INTERVAL • LOGARITHMIC)

shale ratio map seems to have some relationship to the distribution of hydrocarbons. In the area under study, most of the productive and potentially productive wells lie within a sandstone-shale ratio of 2 in Townships 47 and 48, Ranges 2 and 3 and within a sandstone-shale ratio of 4 in Township 48, Range 4, though certain exceptions to this rule exist.

Spontaneous Potential Reduction Factor Map: Clay minerals and clay sized particles are an integral part of petroleum reservoir sands and have a considerable effect on oil recovery (Griffiths, 1952). Clastic reservoir rocks which have an average grain size less than 0.0625 mm. generally contain water (Griffiths, 1952).

An attempt was made in this work to study the effect of the clay content, expressed in terms of spontaneous potential reduction factor (α), on the fluid content and its recovery from the wells drilled and tested in the area under study. The clay content of a sand is also considered as a sensitive indicator of environment, and the spontaneous potential reduction factor map may therefore be used to help determine the environment of deposition.

Figure 11 is a spontaneous potential reduction factor contour map of the basal Belly River sandstone. A relationship between α values and fluid content of the sandstones is apparent. Most of the hydrocarbon-bearing wells in sandstone body 9 are enclosed by the 0.6 (60×10^{-2}) contour line. Both hydrocarbon-bearing and dry wells fall between the 0.6 and 0.5 contour lines and practically no productive wells exist outside the 0.5 contour line. In terms of actual spontaneous potential measured in the well it would mean that

for the sandstone to be productive, it should have at least -72 millivolts of spontaneous potential assuming that the mud filtrate has a resistivity of 5 ohm-m at $64^{o}F$. A sandstone with spontaneous potential in the range -72 to -60 millivolts may or may not be productive while one with spontaneous potential below -60 millivolts is not likely to be productive.

Most of the hydrocarbon bearing wells in sandstone body 7 lie within 0.4 contour line. The area between 0.4 and 0.2 contour line may contain hydrocarbon bearing wells while little or no prospects exists in the area lying outside 0.2 contour line.

For the remaining sandstone bodies, the relationship is not obvious and it can only be said that most of the dry wells have comparatively lower values of α than the productive ones.

It should be noted that these figures are approximate as the spontaneous potential was not corrected for various factors such as the true resistivity of the sandstone, resistivity of the invaded zone, bore hole effects etc. Further, the relation α , a ratio of pseudo static potential to static potential is only an empirical measure of the clay content of a sandstone.

From the environmental point of view, the sandstone bodies are cleaner in their central portion where they are thick, become progressively more shaly towards the peripheries and eventually pass into shale. The study of the spontaneous potential reduction factor is thus an independent approach which supports the inferences derived from the isopach, isolith and sandstone-shale ratio maps. The spontaneous potential reduction factor map may thus be considered as an important stratigraphic tool in studying the

behavior of the fluids in the sandstone reservoir and also in inferring the environment of deposition.

Vertical Variability Map: Lithofacies maps which show the arrangement of rocks in a vertical sense are called vertical variability maps. The number of discrete beds of a given lithological type, such as number of discrete sandstones (Krumbein and Nagel, 1953; Forgotson, 1954) is a convenient measure of vertical variability. The vertical distribution of rock characteristics within a stratigraphic unit may be very significant in understanding the depositional environment. Maps of the number of sandstones often indicate the occurrence of stratigraphic traps due to sandstone pinch outs or facies changes (Forgotson, 1960).

In the present study, instead of counting the discrete sandstone beds, the number of shale beds within the basal Belly River sandstone were counted. Figure 12 is a contour map of the number of shale beds. Trends strike northeast to north. This may suggest that the fluctuating strand line along which shale beds would interfinger with sandstone also had this trend. The long axes of the sandstone bodies have a similar strike (Figure 9). A comparison of the isopach map of the basal Belly River sandstone (Figure 8) with the vertical variability map indicates that the thicker sandstones may have more shale beds than the thinner ones. This may be due to the composite nature of the thicker sandstone bodies where individual sandstone beds are stacked one above another with intervening shale beds.

The vertical variability map used in this study may suffer from a serious drawback. All the "shale beds" identified

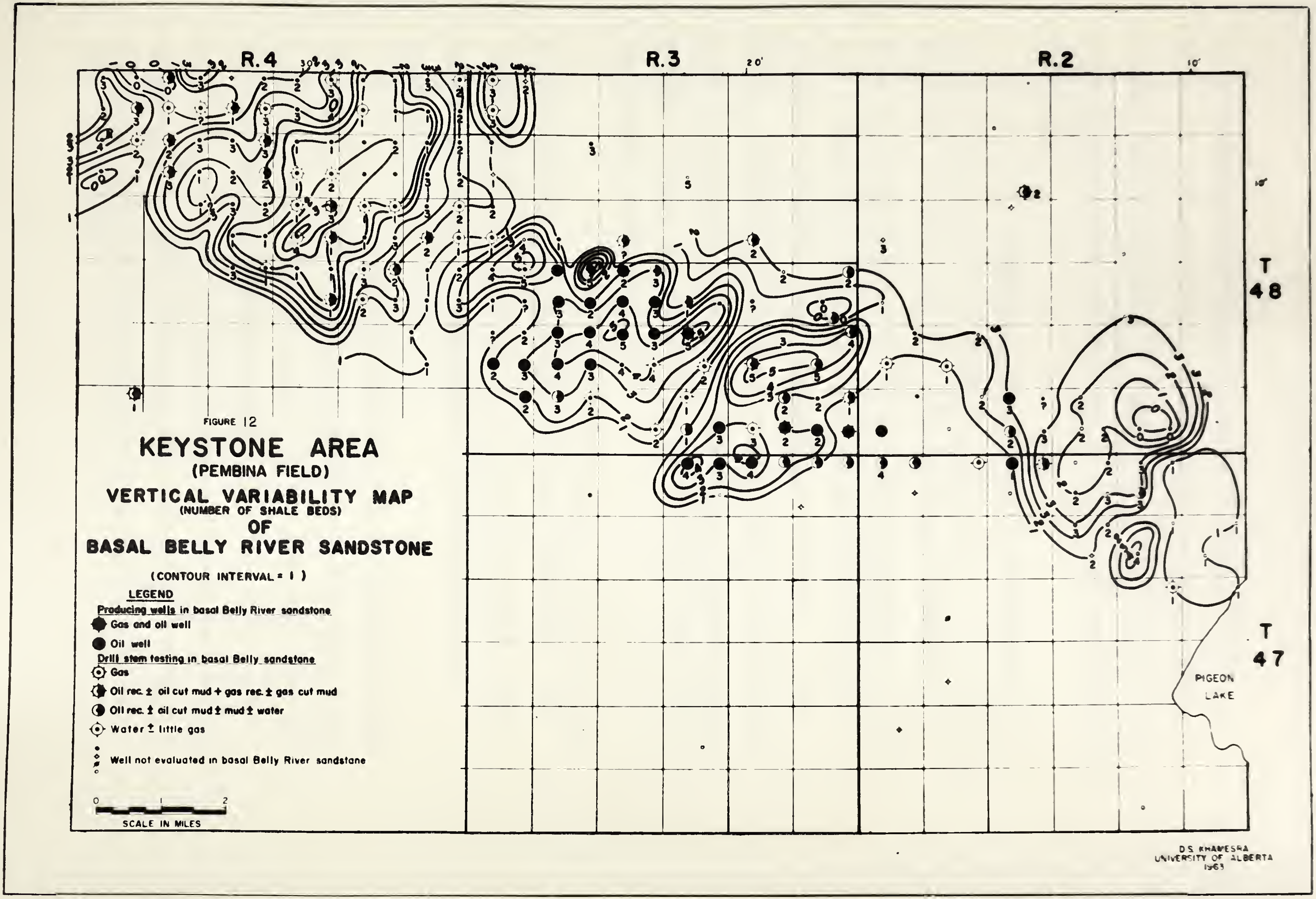


FIGURE 12
KEYSTONE AREA
(PEMBINA FIELD)
VERTICAL VARIABILITY MAP
(NUMBER OF SHALE BEDS)
OF
BASAL BELLY RIVER SANDSTONE

on the spontaneous potential curve may not be shales. Tight calcareous sandstones may equally reduce the spontaneous potential response and may be mistaken for shales, as discussed earlier. This would seriously affect interpretation of the vertical variability and facies maps.

Shaliness Map: The presence of dispersed clay greatly affects the flow of fluids in permeable rocks. An increase in the amount of clay or shaliness in the matrix of a permeable bed reduces the overall pore diameter and decreases the permeability to the flow of fluids resulting in poor fluid recovery when the bed is penetrated and tested. The shaliness should, therefore, provide valuable information regarding the ease with which a reservoir will yield its contained fluids. The determination of shaliness (m_s) of a sandstone using an electrical log and the theoretical basis underlying it will be discussed later.

Figure 13 shows the variation of shaliness (m_s) of the basal Belly River sandstone in the area under study. The contour intervals are logarithmic. The map agrees closely, as was expected, with the spontaneous potential reduction factor map (Figure 11).

The wells lying within the 0.1 isopleth in sandstone bodies 9 and 10, and wells lying within the 0.2 isopleth in the remaining bodies are either productive or indicated production while testing. The interval between the 0.1 and 0.2 isopleths in sandstone bodies 9 and 10, and between the 0.2 and 0.4 in the remaining sandstone bodies contain both water wells and wells with indicated production. There is little chance for the productive wells to

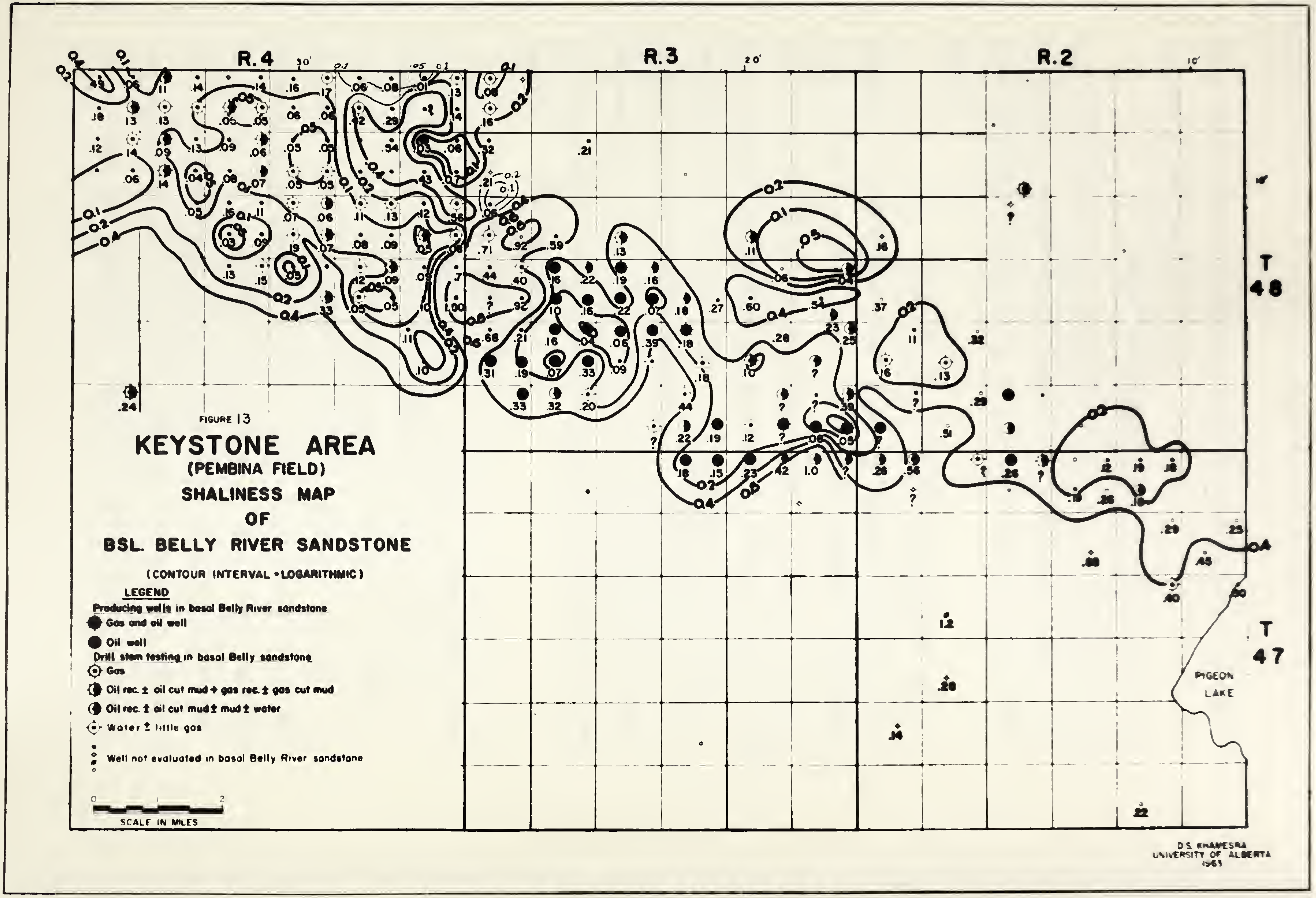


FIGURE 13

KEYSTONE AREA
(PEMBINA FIELD)
SHALINESS MAP
OF
BSL. BELLY RIVER SANDSTONE
(CONTOUR INTERVAL • LOGARITHMIC)

occur above the 0.2 isopleth in sandstone bodies 9 and 10 or the 0.4 isopleth in the remaining bodies.

The wells with gas production only have values of m_s less than 0.18 in the area under study. This may suggest that gas is present in comparatively cleaner parts of sandstone bodies. These clean sandstones are present in the central, thickest parts of the bodies.

A plot of rate of production of gas per day (as measured by drill stem testing) versus shaliness of the bed on semi-log paper was made. The plot shows a general increase in the rate of production with decreasing shaliness, however, there are insufficient data available to reach any firm conclusion. With sufficient control, shaliness values can be related to oil production, gas/oil ratio, pressure build-up, saturation ratio etc. About 50% of the wells in the area under study were tested and with this control such studies can be rewarding. In this project however, no such attempt was made because of time limitations.

Residual Contour Maps

The separation of relatively large-scale systematic changes on a map (called regional) from essentially non-systematic small-scale variations due to local effects, (called residuals) has application in a variety of geological and geophysical fields (Krumbein, 1959). Regional gradients often distort or obscure local anomalies caused by buried ridges, reef, sand bars etc. For this reason, regional effects are often subtracted from the observed values in order to isolate more clearly the features in which we are most interested. There are several methods of doing

this, both graphical and analytical. The relative merits of each method are discussed by Krumbein (1956), Dobrin (1960) and others. In this study, graphical and analytical methods were employed.

Graphical Methods: The simplest method for estimating the regional effect is to draw a series of smooth contours over the observed map to remove the irregularities and reversals in the contour lines. A knowledge of the regional gradient and of the variability of the observed data helps in drawing the smooth contours. The smooth contours represent the regional contour surface and the numerical difference between the observed and smoothed contours at any point represents the residual effect. The smoothed map may be subtracted from the original map by recording the difference in map values at selected grid points and contouring these differences to obtain a separate residual contour map. A residual structural contour map on the top of the Lea Park Shale was prepared (Figure 14) in this way to investigate the relationship between the paleotopography and the positions of sand accumulations. A comparison between the isopach and isolith maps of the basal Belly River sandstone (Figures 8 and 9) and Figure 14 does not seem to indicate any relationship between the paleotopography and the sand accumulations (Figure 14 overlay). It was felt that a considerable flexibility was possible in smoothing the contours, involving a considerable subjective judgement, and residual features nearly parallel to the regional contours would probably not appear. A residual map was constructed therefore using the less subjective graphical method discussed below.

Regional values may be calculated using an average of observed values on a circle. The residual is the differ-

ence between this average and the observed value at the center of the circle. The principal problem in this method is in the choice of a radius for the circle. This must be large enough that the circle will lie entirely outside any anomaly but not so large as to include irregularities from other sources. In this study a circle 3 inches in diameter (equals 3 miles on the map) was chosen in preparing the residual map and an arithmetic mean of four equally spaced values on the circumference of the circle was taken as the value of the regional at the centre. The difference between this value and the observed value is the residual. Residuals are positive where the observed data are structurally higher than the regional average and negative where the observed data are lower than the regional values. Residuals were calculated for grid points spaced one half mile apart. Figure 15 is the residual contour map on the top of the Lea Park Shale drawn on the principle of the one ring method, discussed above. It shows both positive and negative anomalies which do not seem to bear any relationship with the sand accumulations.

The one ring method discussed above may be elaborated upon by using several concentric rings instead of one, with the averages from rings of different radii having different weights, some of which may be negative. The multi-ring system has a definite advantage in that it is less affected by single values and tends to integrate the result into a smoother picture. However, it was felt that this method would be too time consuming because of the large number of observation points, totalling about 200. An I.B.M. 1620 computer was available and it was considered worthwhile to give a more rigorous analytic treatment to the observed data to attain more accuracy and gain time as well.

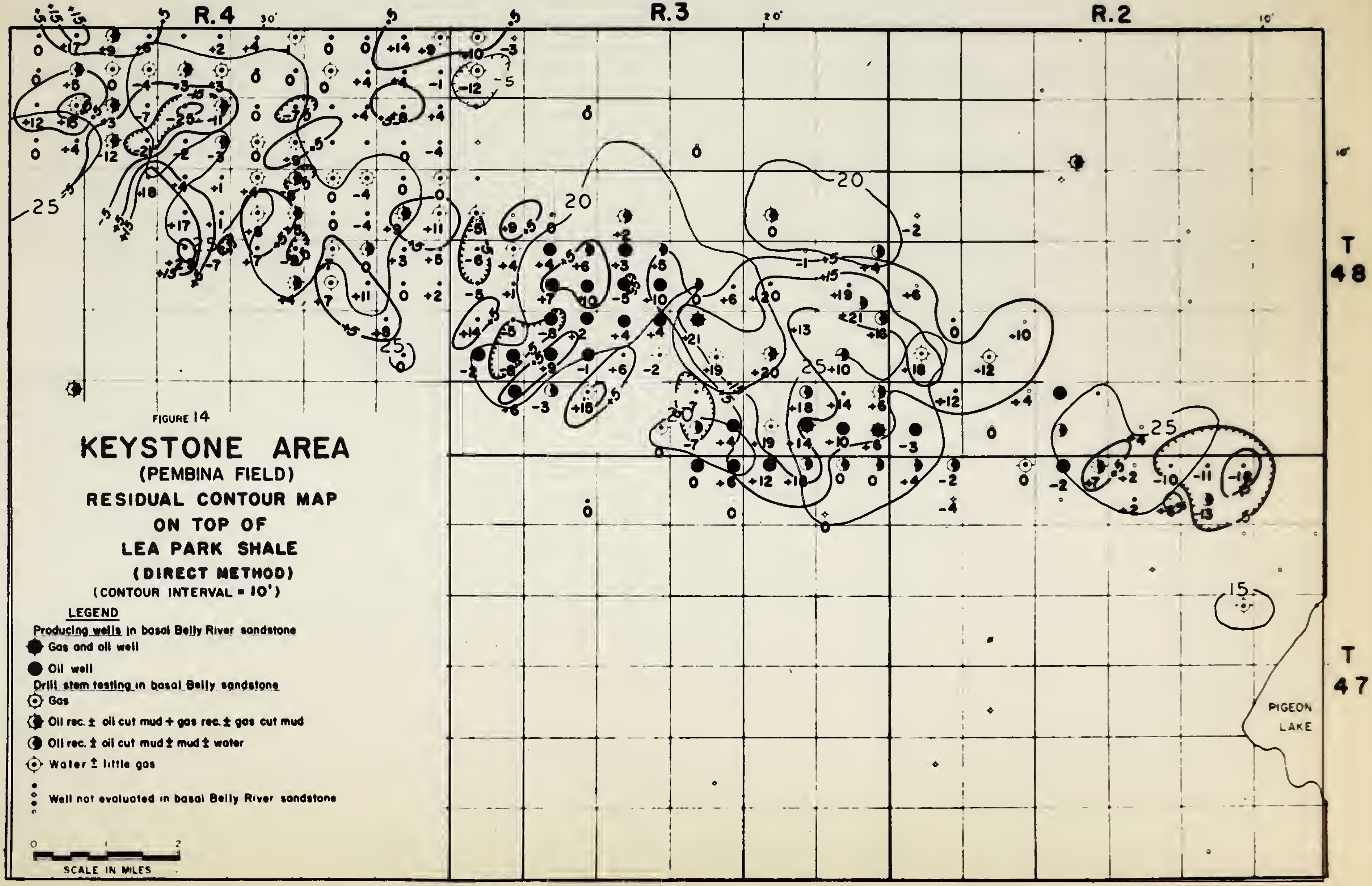


FIGURE An overlay of sand isoliths (See FIGURE 9)

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UNIVERSITY OF ALBERTA
1963

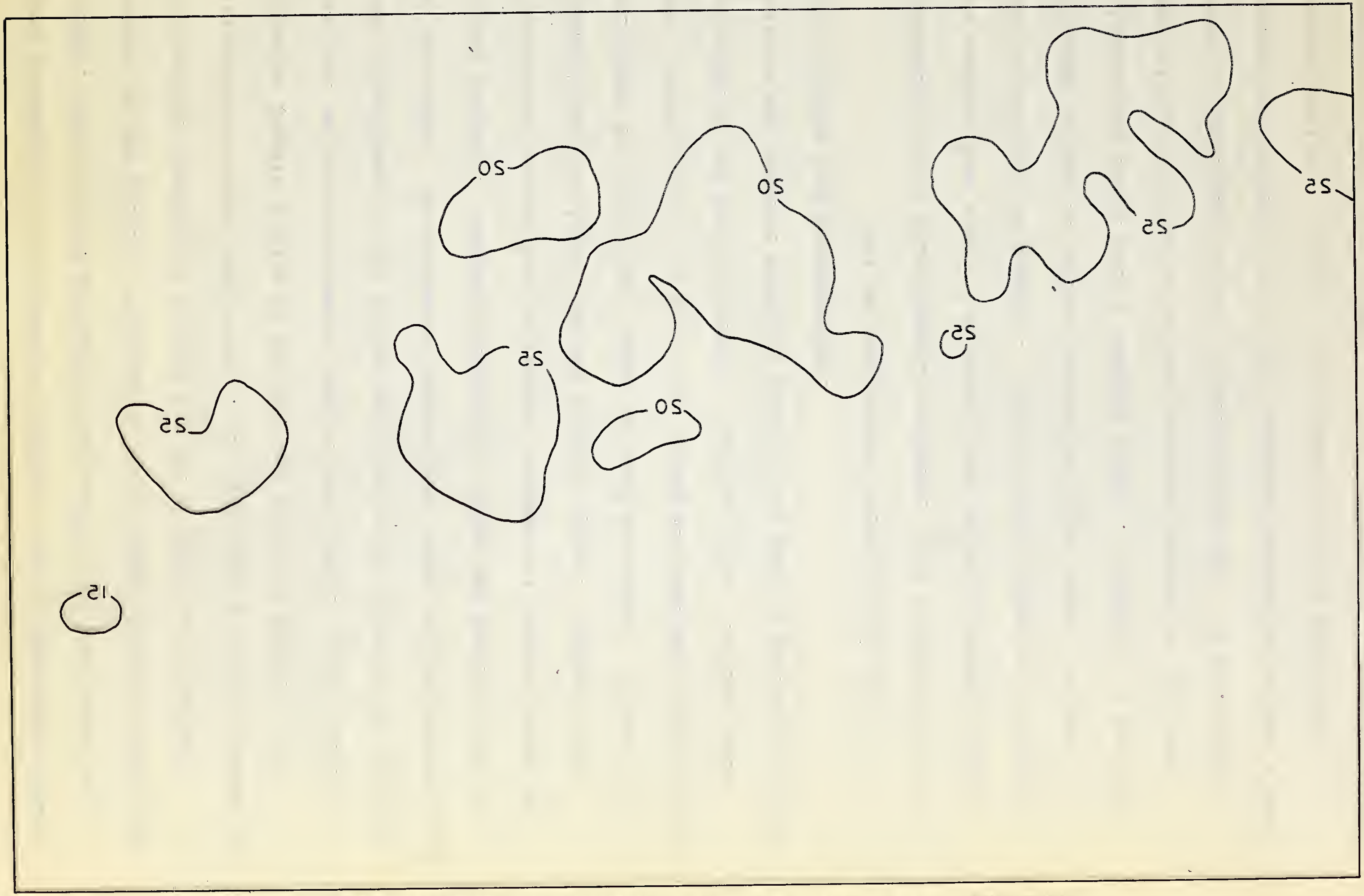
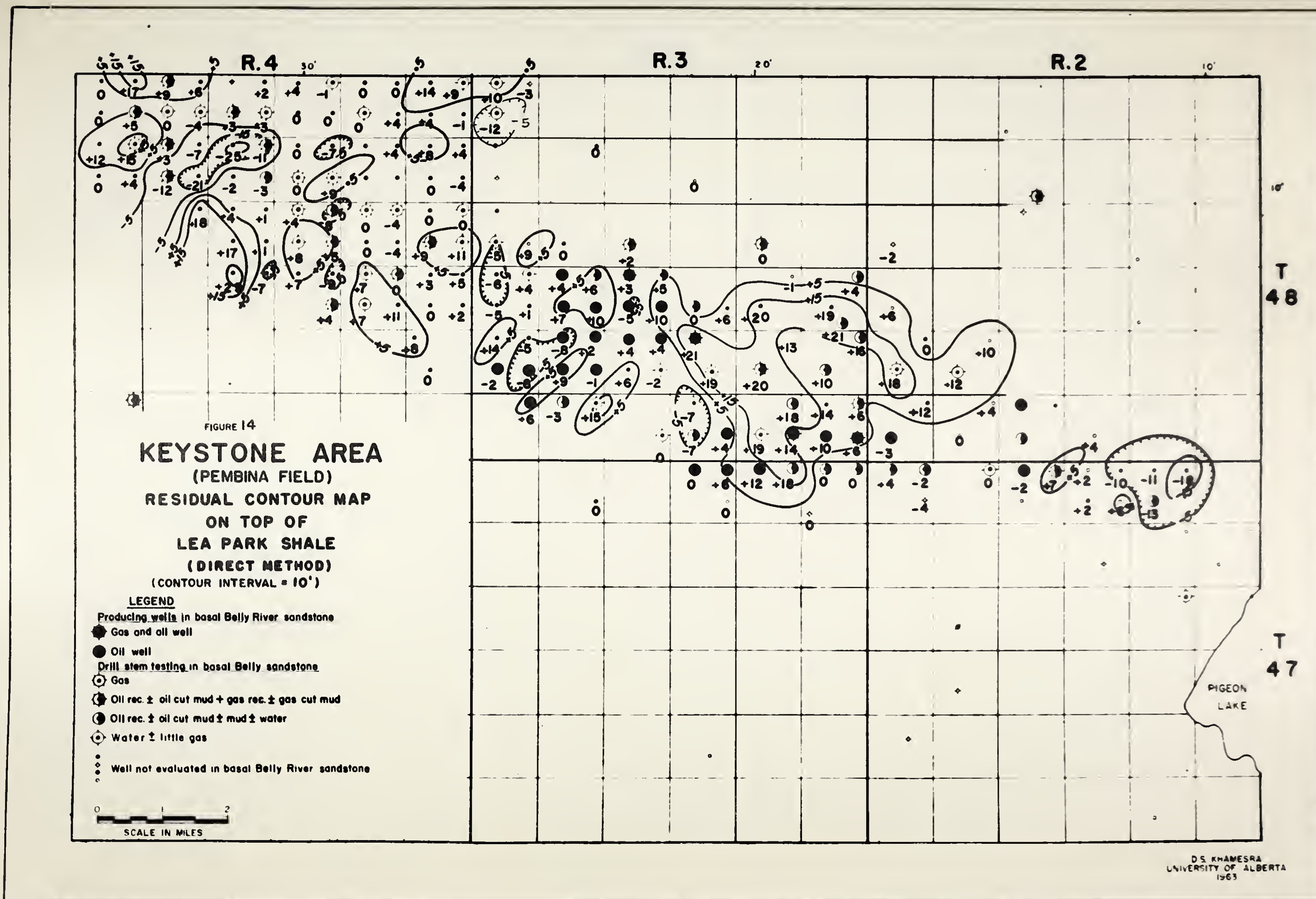


FIGURE An overlay of sand isoliths (See FIGURE 9)


R.4
R.3
R.2
T 48
T 47
PIGEON LAKE
FIGURE 14
KEYSTONE AREA
(PEMBINA FIELD)
RESIDUAL CONTOUR MAP
ON TOP OF
LEA PARK SHALE
(DIRECT METHOD)
(CONTOUR INTERVAL = 10')
LEGEND
Producing wells in basal Belly River sandstone
Gas and oil well
Oil well
Drill stem testing in basal Belly sandstone
Gas
Oil rec. ± oil cut mud + gas rec. ± gas cut mud
Oil rec. ± oil cut mud ± mud ± water
Water ± little gas
Well not evaluated in basal Belly River sandstone
SCALE IN MILES
D.S. KHAMESRA
UNIVERSITY OF ALBERTA
1963

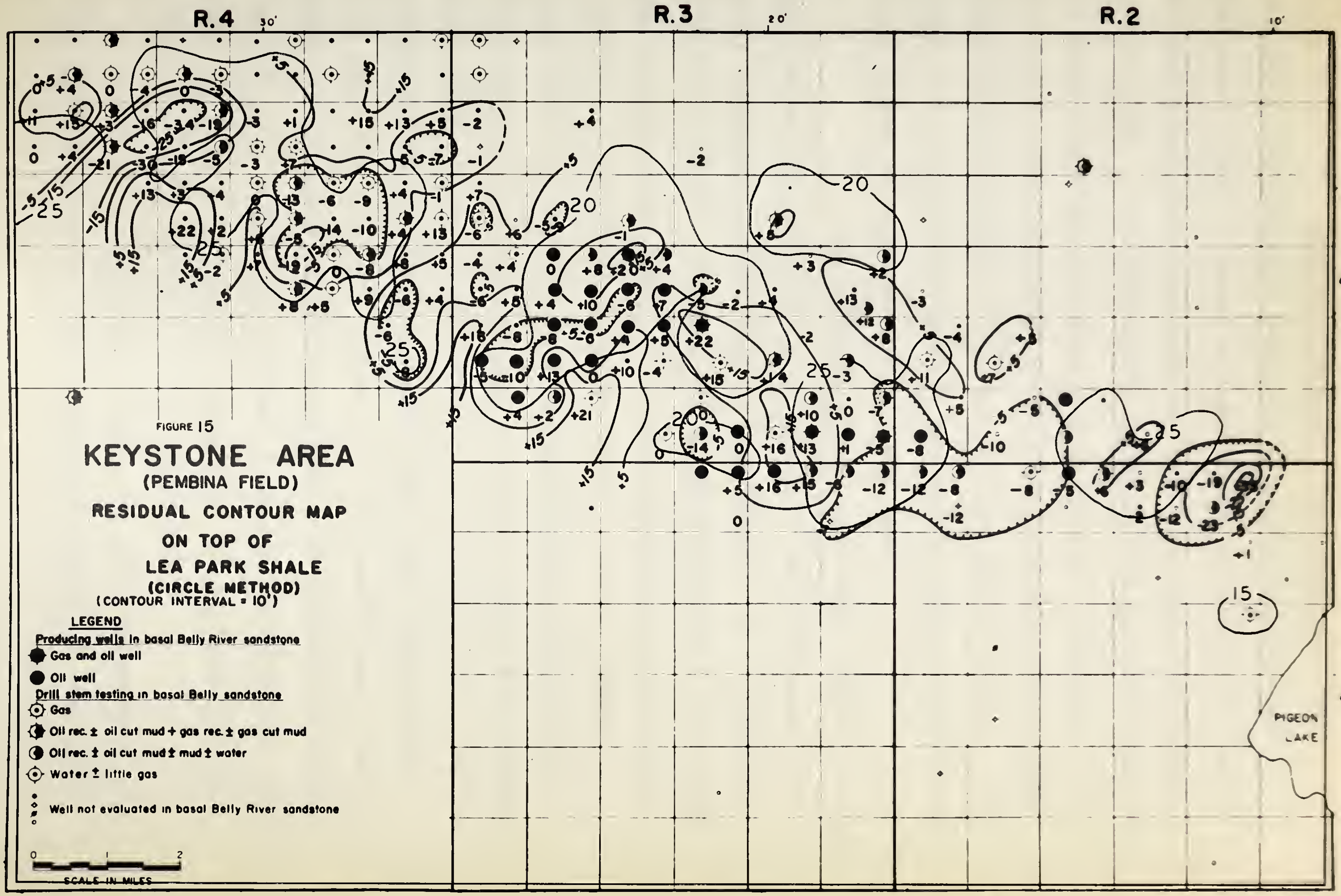


FIGURE An overlay of sand isoliths (See FIGURE 9)

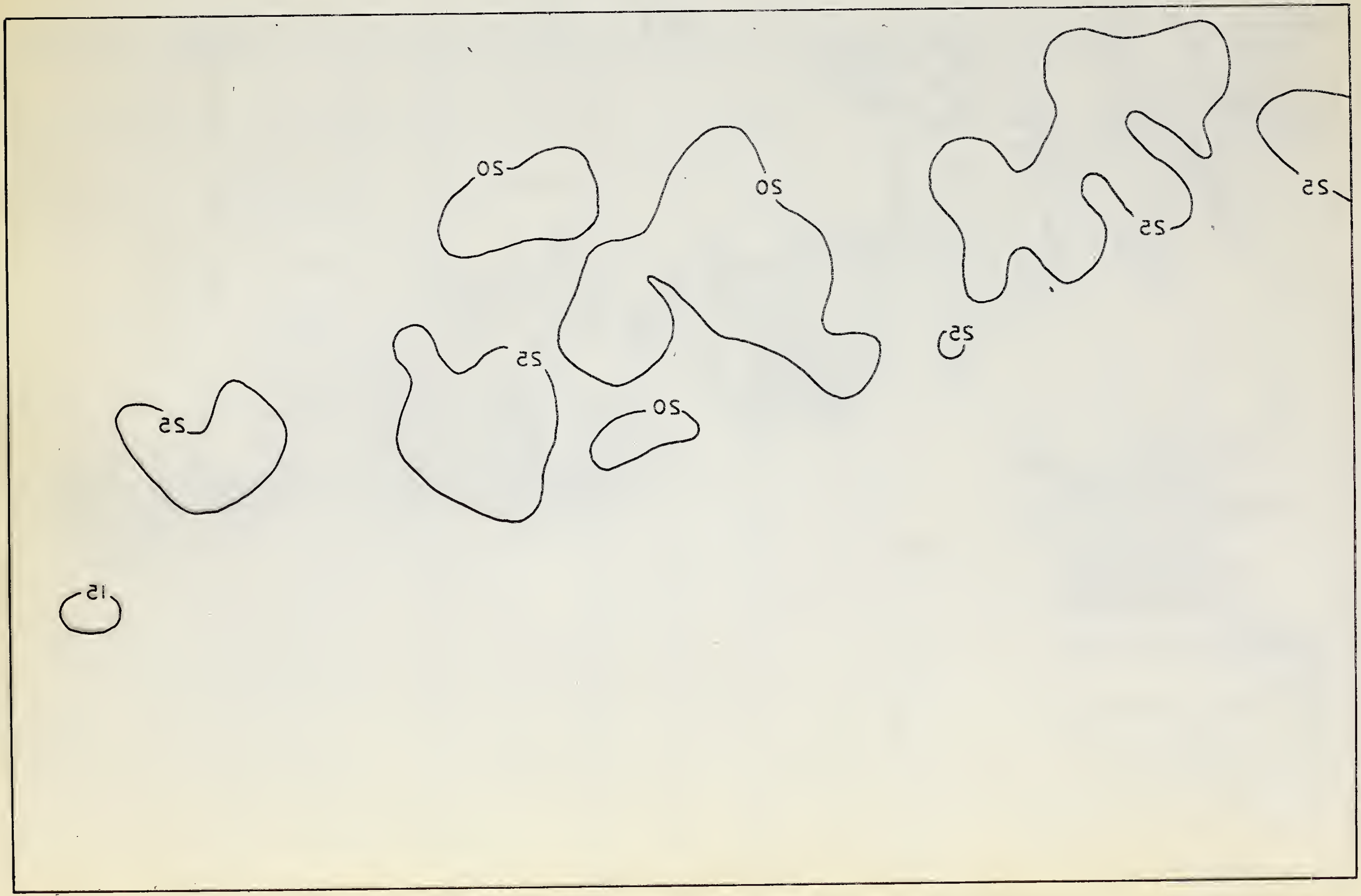


FIGURE An overlay of sand isoliths (See FIGURE 9)

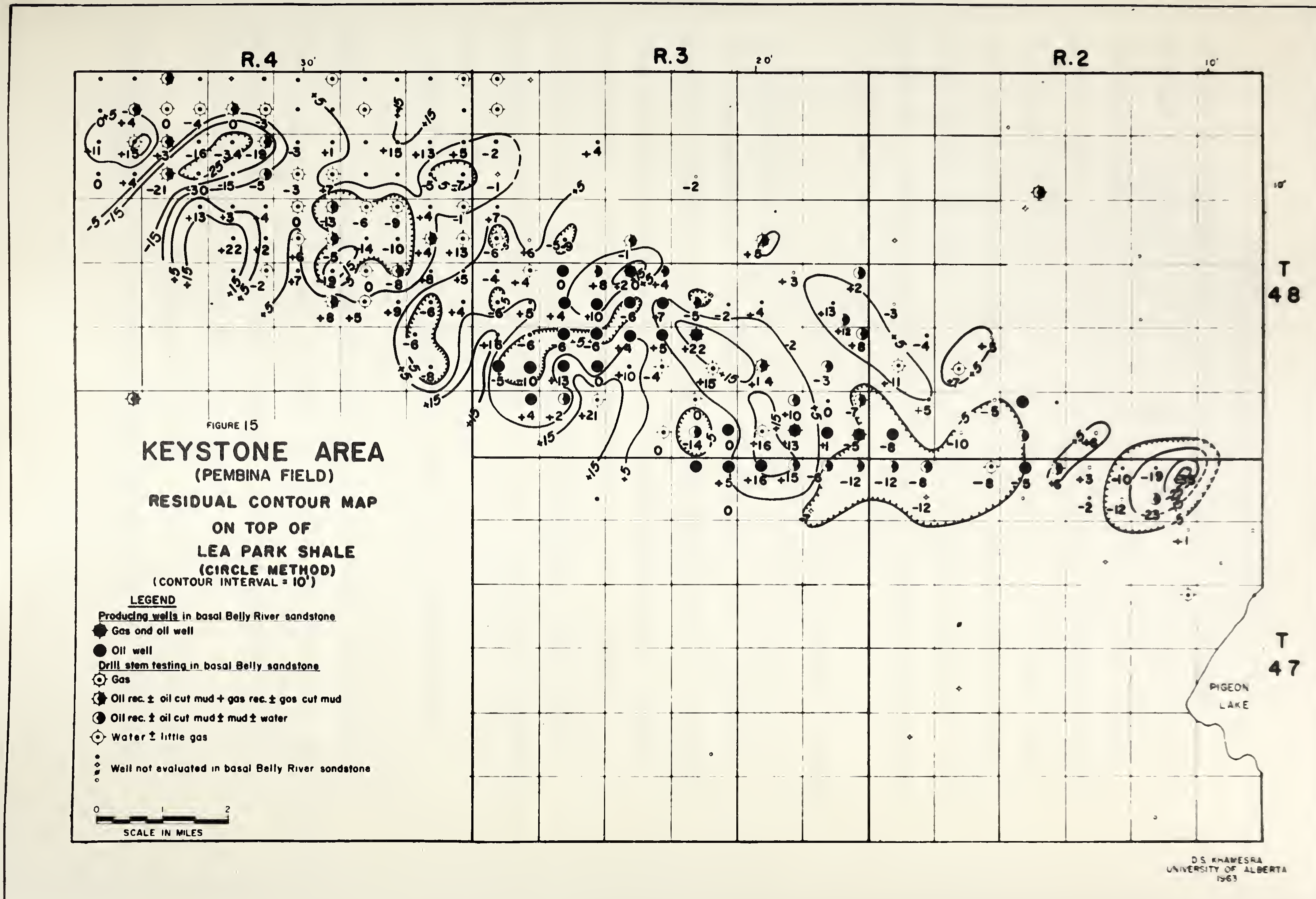


FIGURE 15

KEYSTONE AREA

(PEMBINA FIELD)

RESIDUAL CONTOUR MAP

ON TOP OF

LEA PARK SHALE

(CIRCLE METHOD)

(CONTOUR INTERVAL = 10')

Analytical Methods - Trend Analysis: Trend analysis is the analytical separation of relatively large-scale systematic changes in mapped data (the trend) from essentially non-systematic small scale variations due to local effects (the residual on the trend). It is based on the assumption that any surface that can be contoured can also be expressed by an equation. The equation for the surface can be separated into two parts. The part describing the trend surface is assumed to be a low order polynomial expression. The other part expresses the difference between the complex surface and the trend surface and may involve higher order terms.

Geological data rarely have unique regional surfaces. The simplest type of surface is a plane and it may be regarded as a first approximation to the regional trend pattern. It is desired to find a plane which is the "best fit" to the observed data in the sense that the sum of the squares of the differences between each observed value and its counterpart on the computed plane is at a minimum, or in other words, the residual sum of squares is minimum. Conventional least square methods are available for fitting a plane to the observed data. Where irregularities are marked, a plane may not fit to the observed data and fitting of successive higher order curved surfaces i.e. quadratic, cubic etc. (Figure 16) to the observed data is involved until a sufficiently close fit is obtained. The method of calculating the successive higher order surfaces is sometimes facilitated by employing the method of fitting by orthogonal polynomials, using principle of least squares, described by Oldham and Sutherland (1955).

Orthogonal polynomials are most conveniently used when observations can be made on a rectangular grid. De Lury (1950)

lists the orthogonal polynomials up to $n = 26$, which permit routine analysis, by high speed computers, of maps with as many as 26 rows and 26 columns in the grid.

Since the data are irregularly distributed over the map area, orthogonal polynomials offer no special advantage, and a least squares power series method was adopted in order to determine the trend surface.

Maps with very limited control or with highly irregular control point spacing do not justify formal polynomial analysis, but such is not the case in the present study.

The method for computing the surface of best fit and the mathematical theory associated with such analysis is outlined in Appendix J.

Simplified Trend Determination Method: A simplified method for computing the amount of variability accounted for by the various trend surfaces was followed (for programming, see Appendix O). The procedure involved the following steps:

1. Sum the squares of each individual observation of the original data.
2. Square the sum of the individual values and divide it by

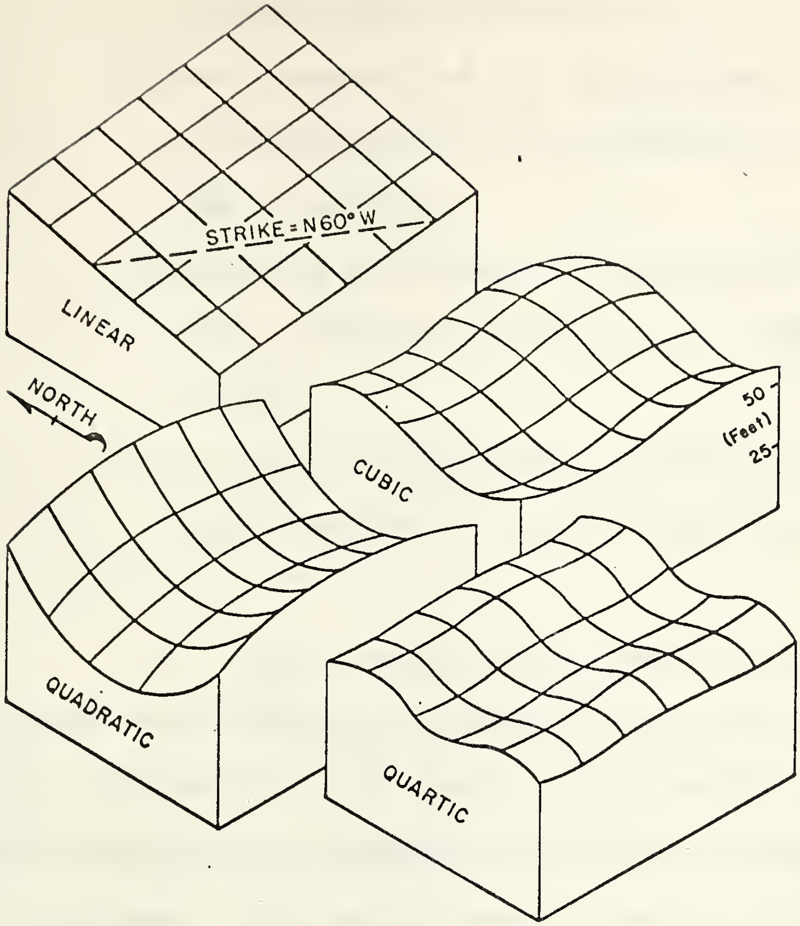


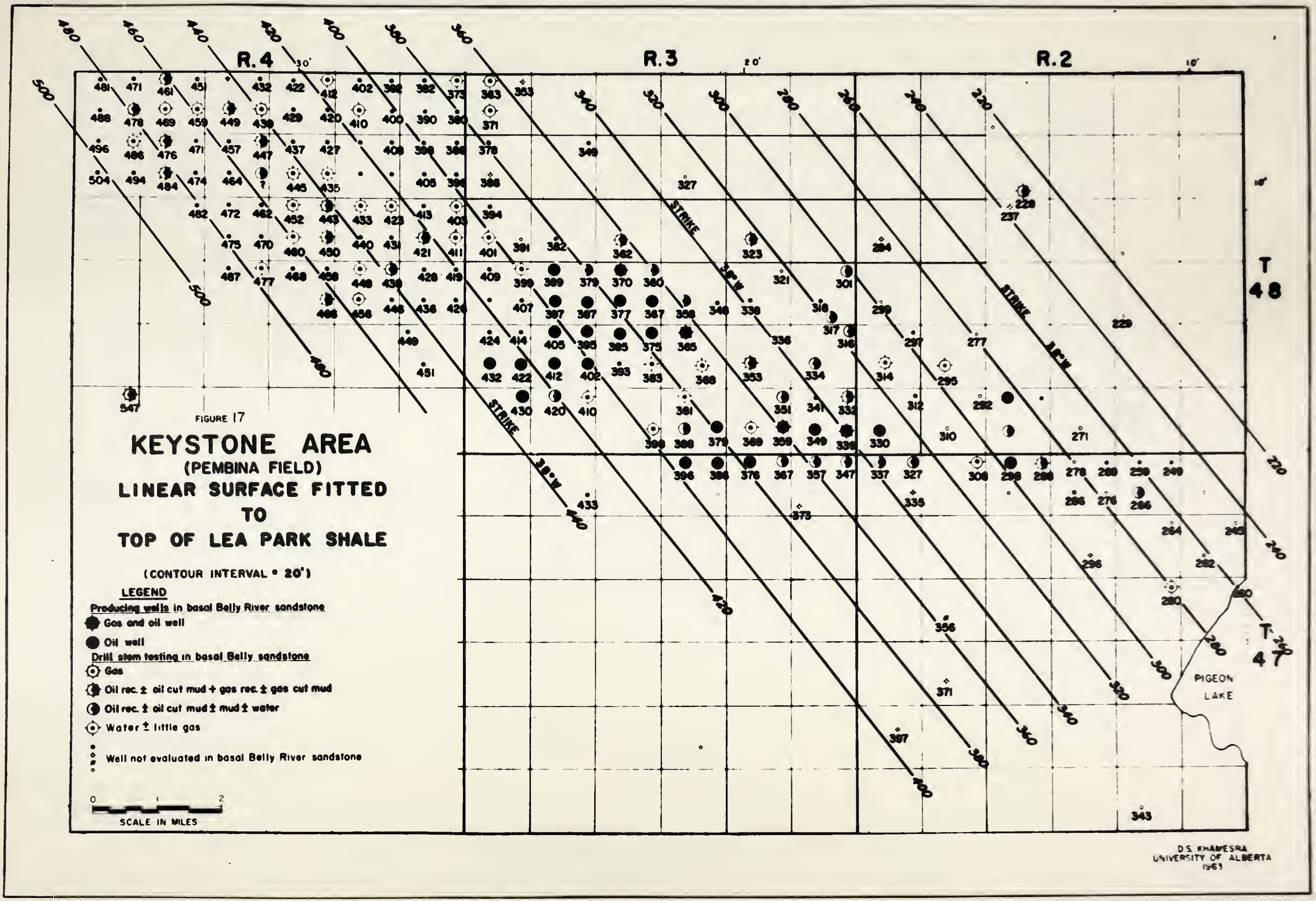
FIGURE 16 Linear, quadratic, cubic and quartic surfaces
(After Krumbein, 1956)

the total number of observations.

3. Sum of squares (S.S.) of original data is determined by subtracting the value obtained from step (2) from that of step (1).
4. Obtain the sum of squares of each individual observation of trend values on the linear, quadratic and cubic surfaces.
5. Then ratio of the variations calculated in step (4) to that calculated in step (3) were obtained.

The structure contour map on the top of the Lea Park Shale was analyzed for its regional and local (or residual) components. Regional trend surfaces of linear, quadratic and cubic order and the deviations (or residuals) from each one of these trend surfaces were calculated. Trend surface analysis was carried out using a least squares power series analysis.

Figure 17 is a linear trend surface map on the top of the Lea Park Shale. It is a plane surface tilted to the southwest at about 25 feet to the mile. The strike of the linear surface is N 38°W. The corresponding residual map obtained by subtracting the computed trend values from the observed values, is shown in the Figure 18. A comparison of the isopach and isolith maps of the basal Belly River sandstone (Figures 8 and 9) with the residual map does not seem to indicate any relationship between the two; in other words, it



R.4
R.3
R.2
T 48
T 47
PIGEON LAKE
STRIKE 38°W
FIGURE 17
KEYSTONE AREA
(PEMBINA FIELD)
LINEAR SURFACE FITTED
TO
TOP OF LEA PARK SHALE
(CONTOUR INTERVAL = 20')
LEGEND
Producing wells in basal Belly River sandstone
Gas and oil well
Oil well
Drill stem testing in basal Belly sandstone
Gas
Oil rec. ± oil cut mud + gas rec. ± gas cut mud
Oil rec. ± oil cut mud ± mud ± water
Water ± little gas
Well not evaluated in basal Belly River sandstone
0 1 2
SCALE IN MILES
D.S. KHAMESRA
UNIVERSITY OF ALBERTA
1963

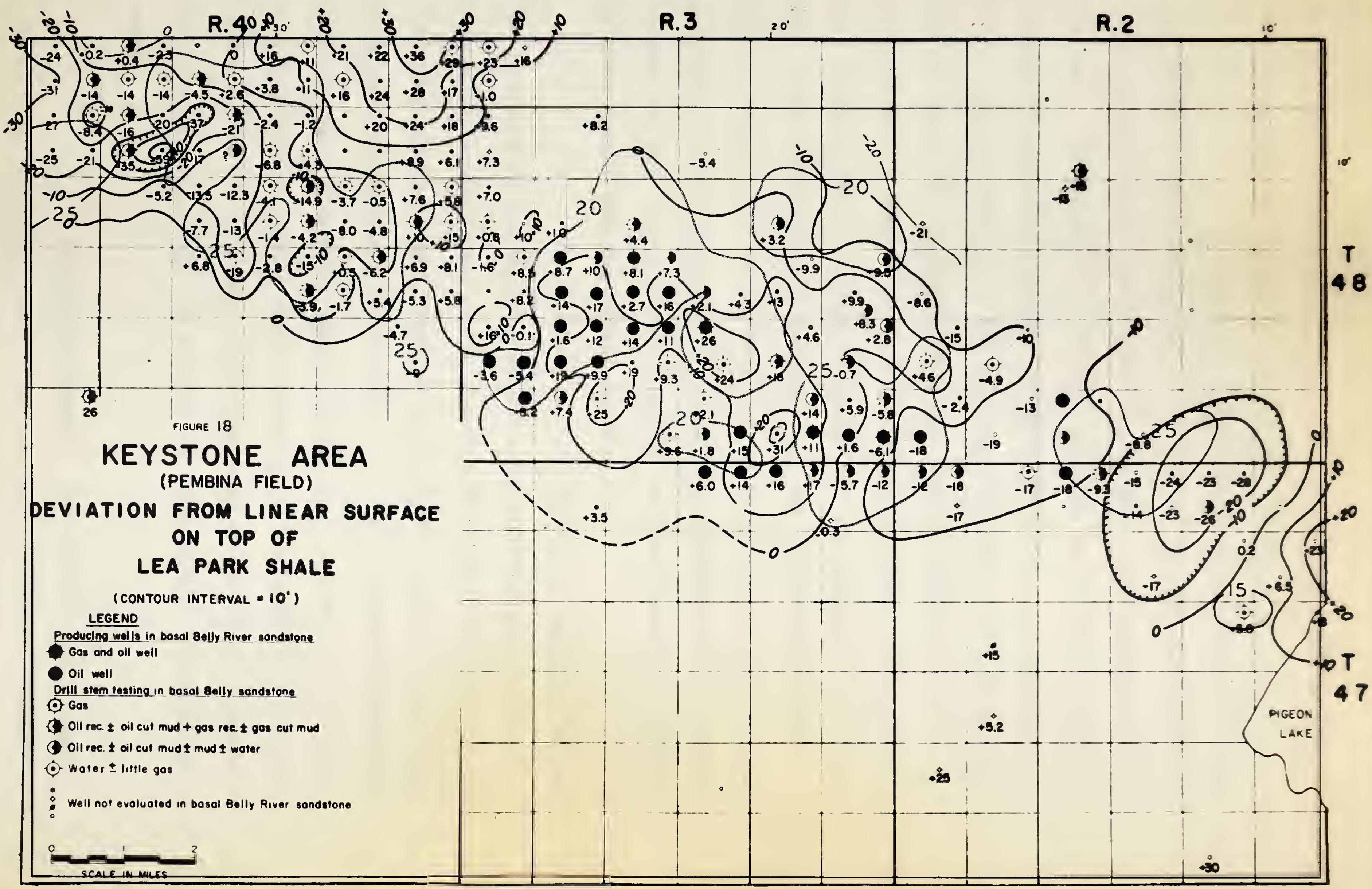
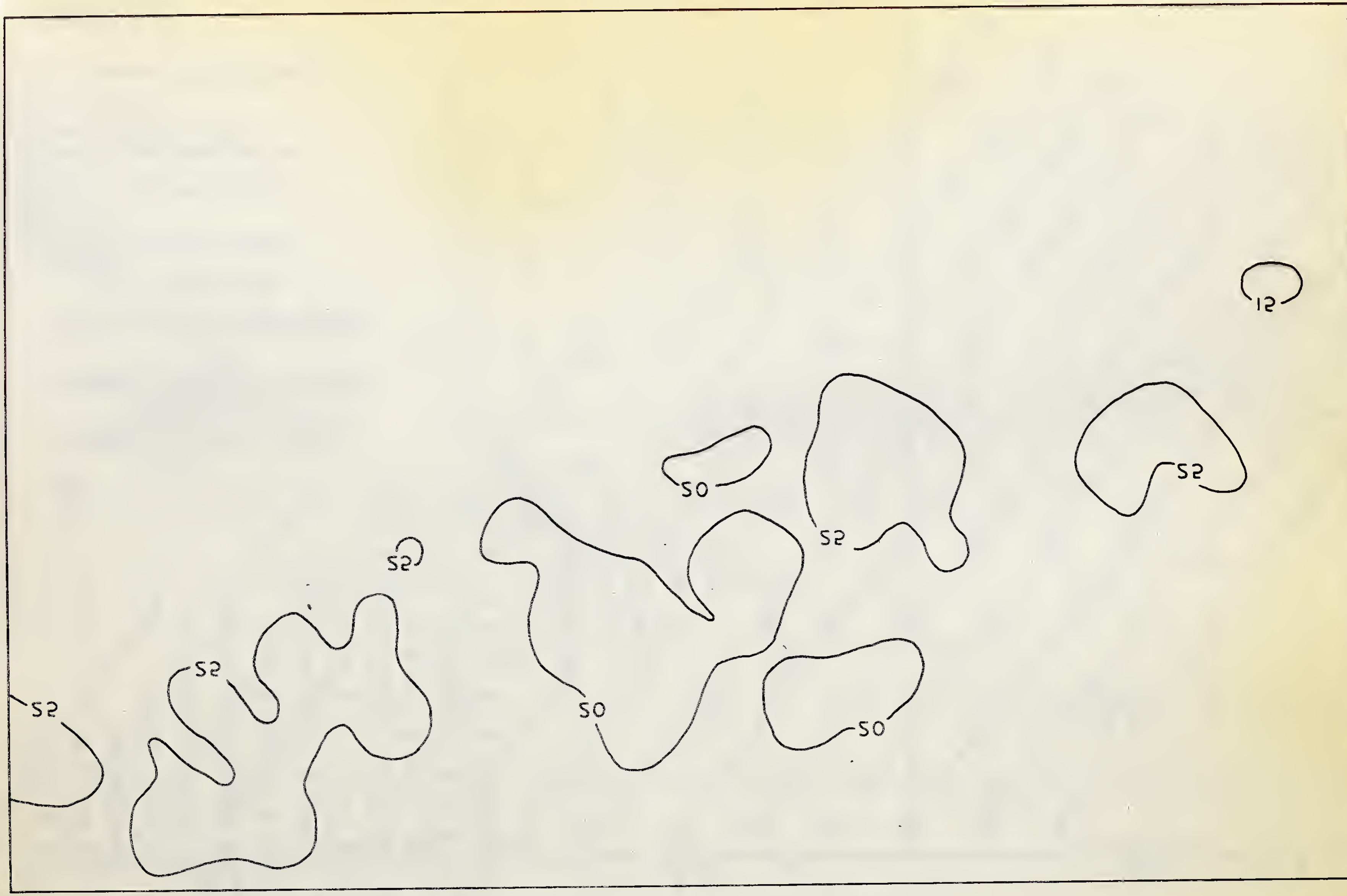


FIGURE An overlay of sand isoliths (See FIGURE 9)

D.S. KHAMESRA
UNIVERSITY OF ALBERTA
1963

FIGURE An overlay of sand isoliths (See FIGURE 9)



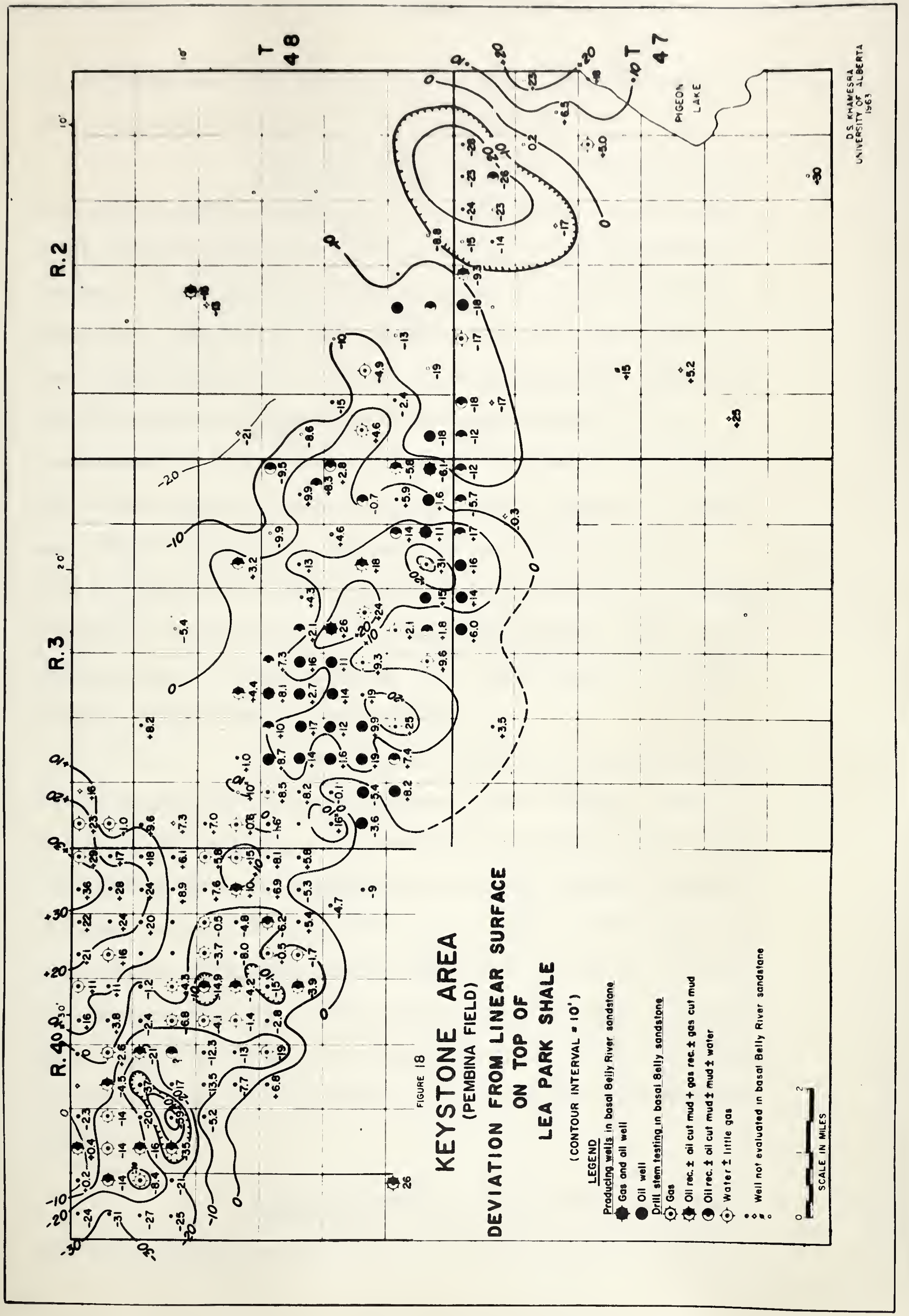


FIGURE 18
KEYSTONE AREA
(PEMBINA FIELD)
DEVIATION FROM LINEAR SURFACE ON TOP OF LEA PARK SHALE
(CONTOUR INTERVAL = 10')

is not likely that the sand accumulations were controlled by the paleotopography on the top of the Lea Park Shale.

A quadratic trend surface on the top of the Lea Park Shale is shown in Figure 19. It is very similar to the linear trend surface except for its minor curvature in the eastern half of the area. The deviation (residual) map from the quadratic surface (Figure 20) also shows similar anomalies as on the linear surface. A cubic trend surface map on the top of the Lea Park Shale (Figure 21) and the deviation (residual) from this surface (Figure 22) are respectively similar to those of the quadratic maps. This suggests that trend components higher than linear do not dominate the deviation map. This is indicated by the fact that the ratios described in step 5, page 50, are 81.86, 83.22 and 84.12 for the linear, quadratic and cubic surfaces respectively. The ratio approaches 100 as the fit becomes perfect. In this case the cubic surface appears to be only slightly better than the linear surface.

The residual sum of squares was employed to test the closeness of fit of observed and calculated surfaces. This is a measure of the deviation of the observed data from the plane of best fit. The residual sum of squares on the linear, quadratic and cubic polynomial surfaces are 68.5×10^3, 53.7×10^3, 44×10^3 respectively (Appendix M). This means that an increasingly better fit is obtained with increasingly higher order components as indicated by a reduction in the sum of the squares. The higher components tend to dominate the deviation map but their contribution to the complete trend map may be small.

<u>Concluding Remarks</u>: The residual contour maps prepared using both the graphic and the analytic methods yielded

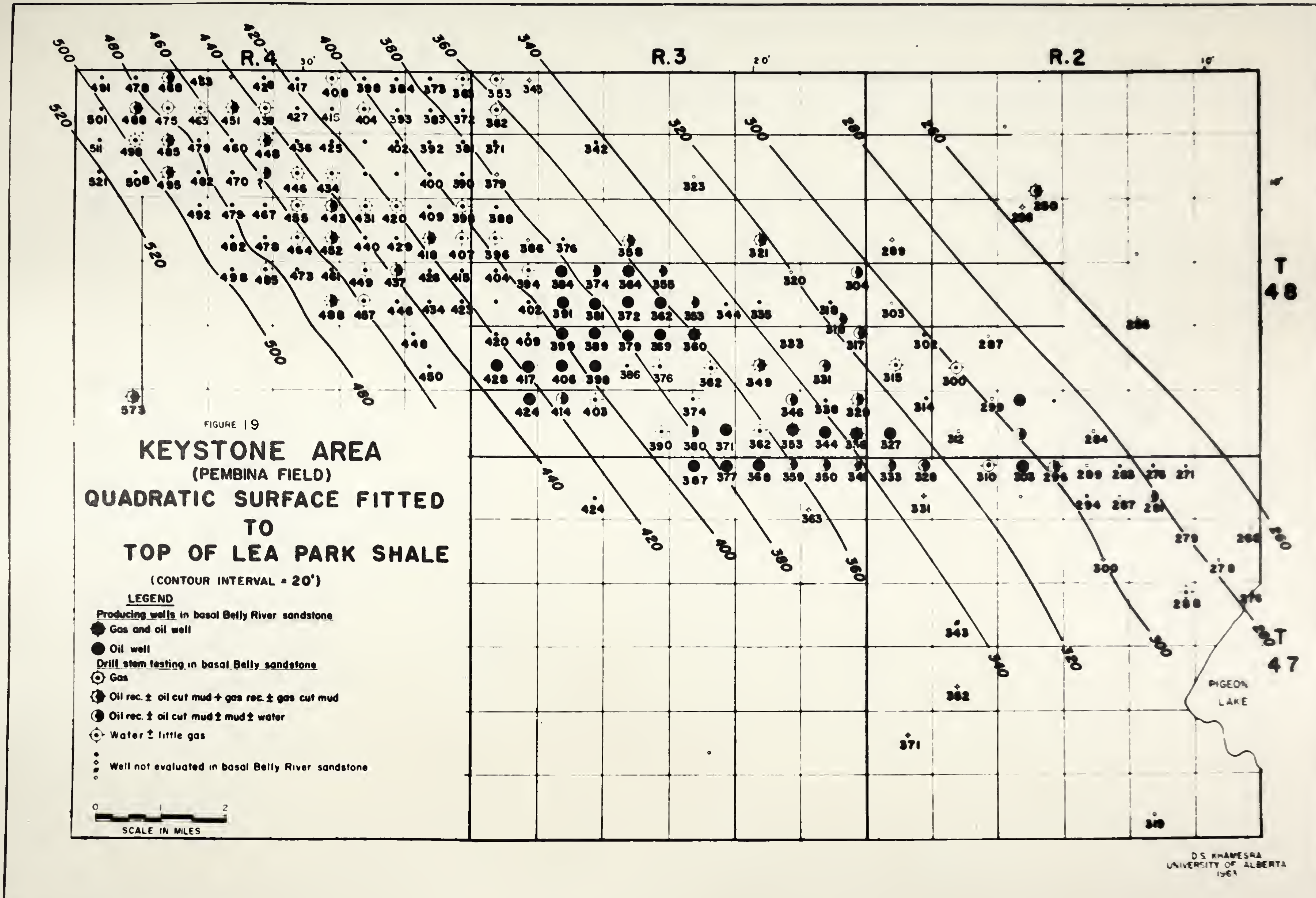


FIGURE 19
KEYSTONE AREA
(PEMBINA FIELD)
QUADRATIC SURFACE FITTED
TO
TOP OF LEA PARK SHALE
(CONTOUR INTERVAL = 20')
LEGEND
Producing wells in basal Belly River sandstone
Gas and oil well
Oil well
Drill stem testing in basal Belly sandstone
Gas
Oil rec. ± oil cut mud + gas rec. ± gas cut mud
Oil rec. ± oil cut mud ± mud ± water
Water ± little gas
Well not evaluated in basal Belly River sandstone
SCALE IN MILES
R.4
R.3
R.2
T 48
T 47
PIGEON LAKE
D S KHAMESRA
UNIVERSITY OF ALBERTA
1967

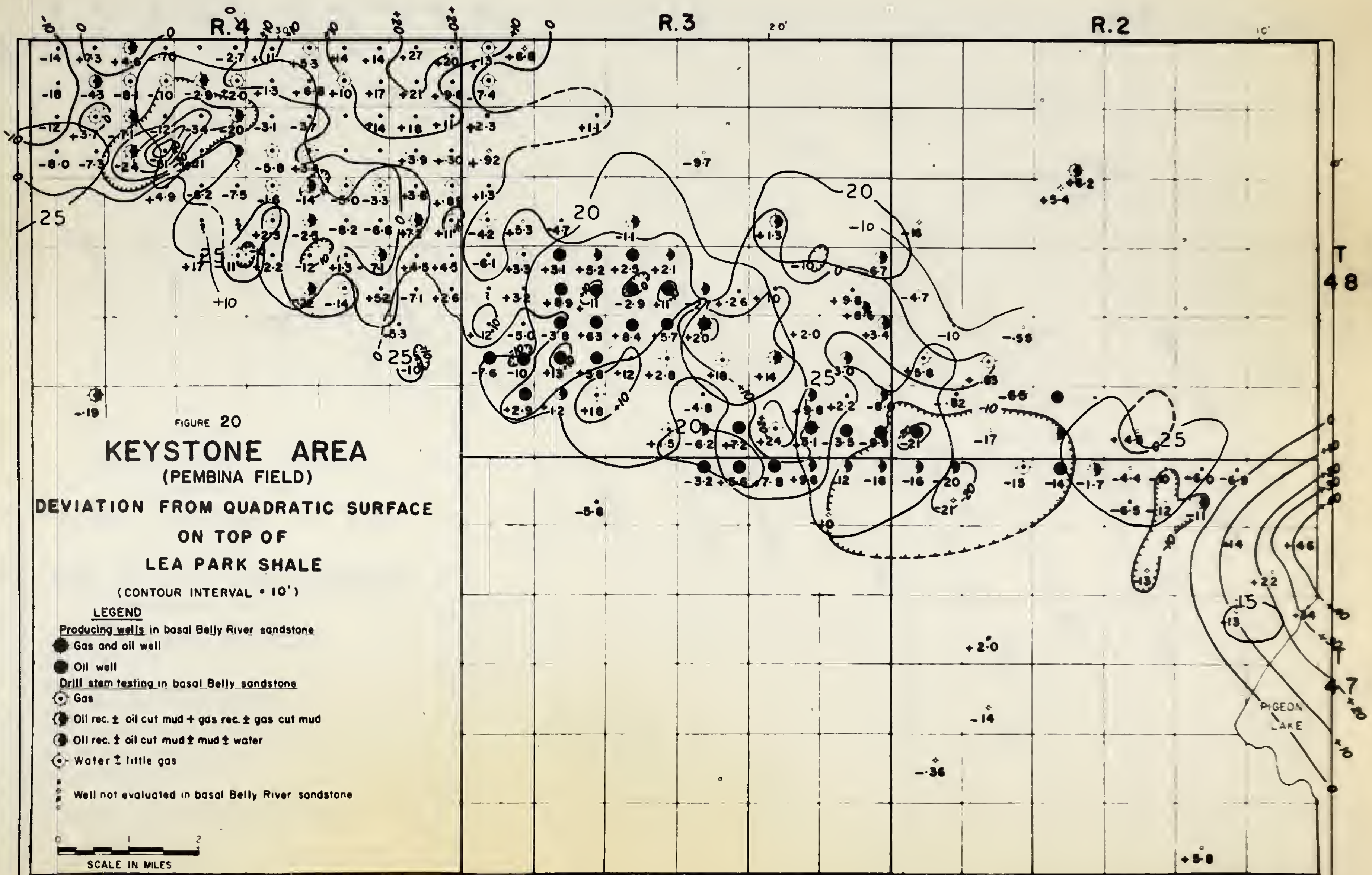
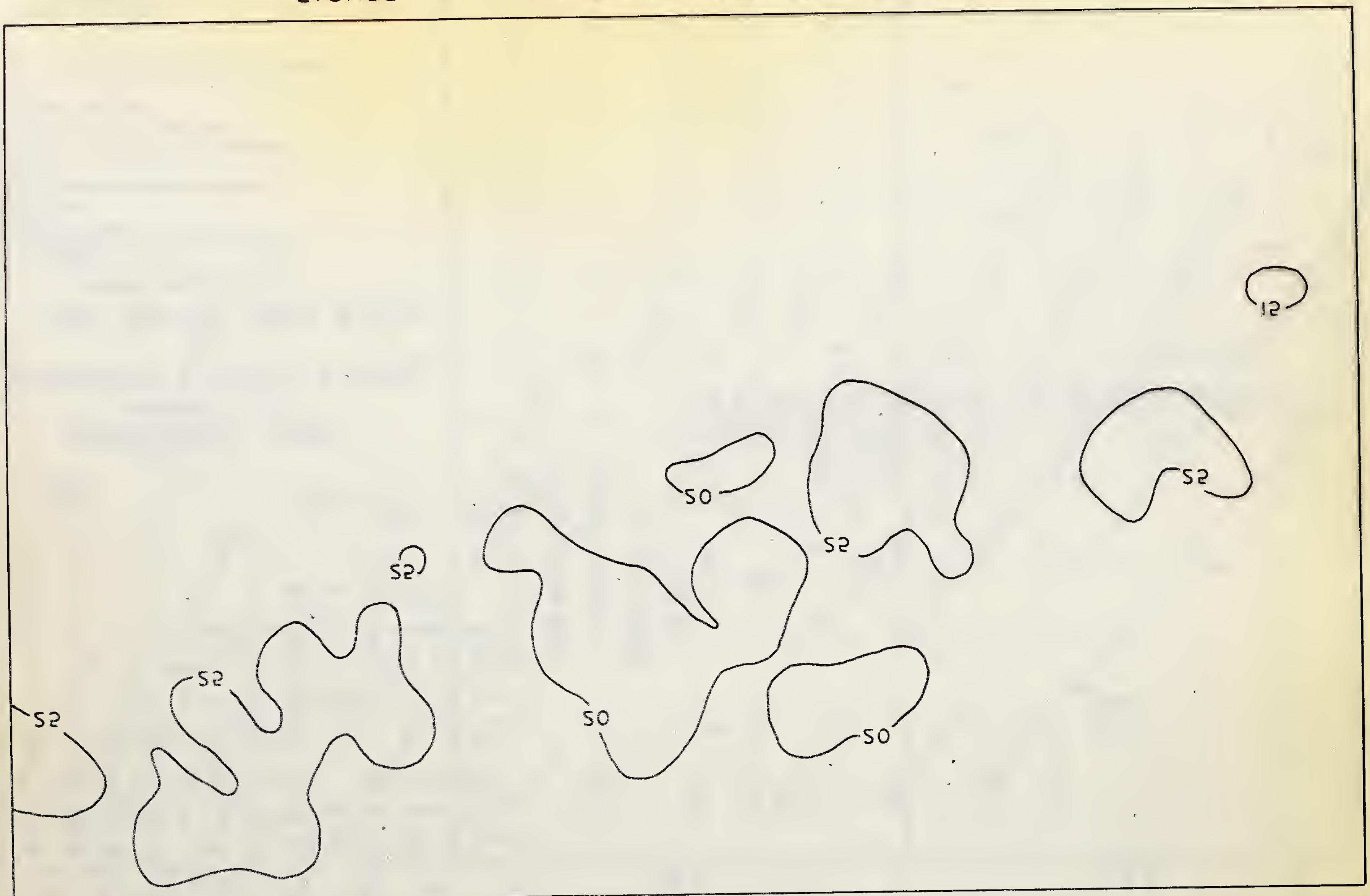


FIGURE An overlay of sand isoliths (See FIGURE 9)

FIGURE An overlay of sand isoliths (See FIGURE 9)



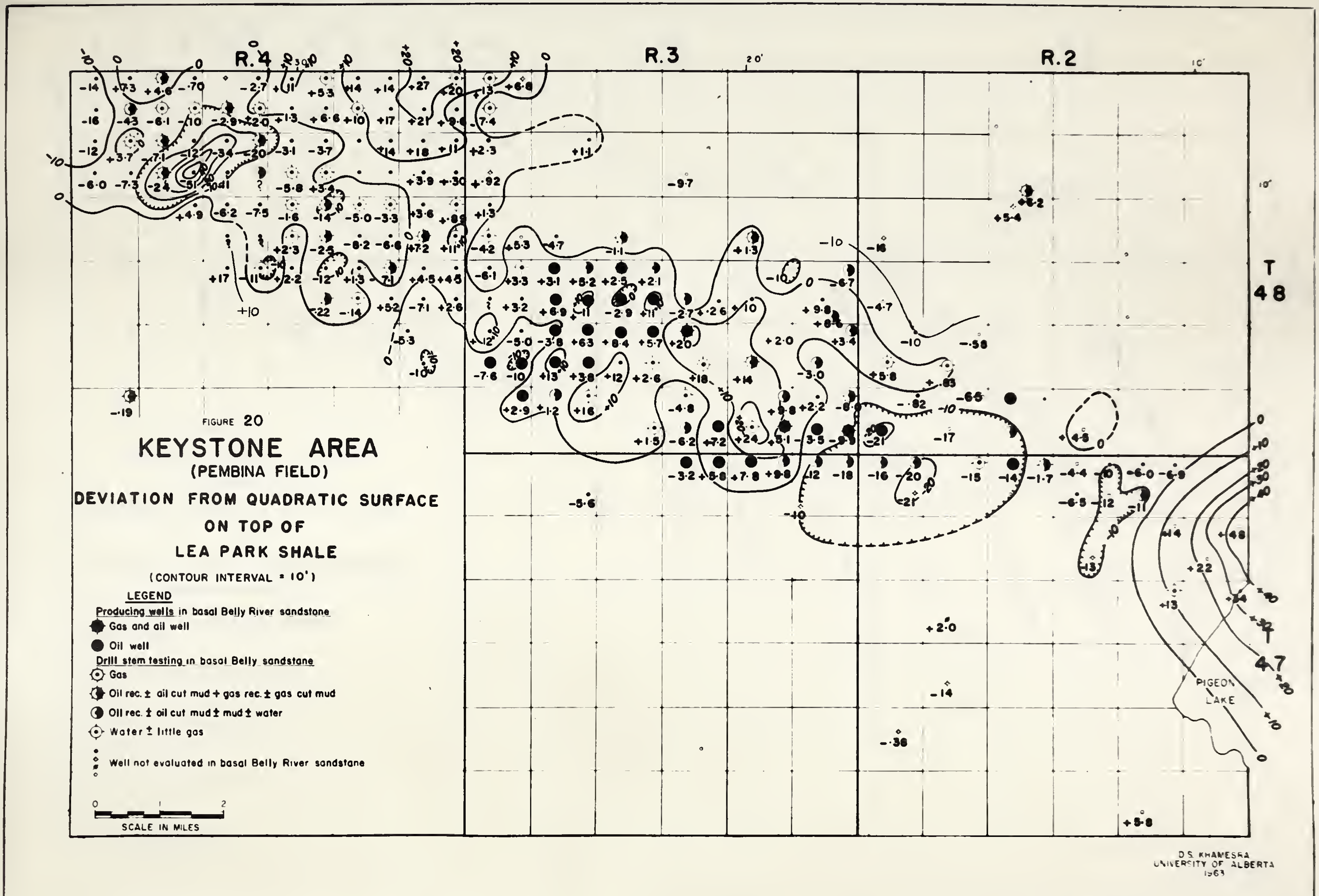


FIGURE 20

KEYSTONE AREA

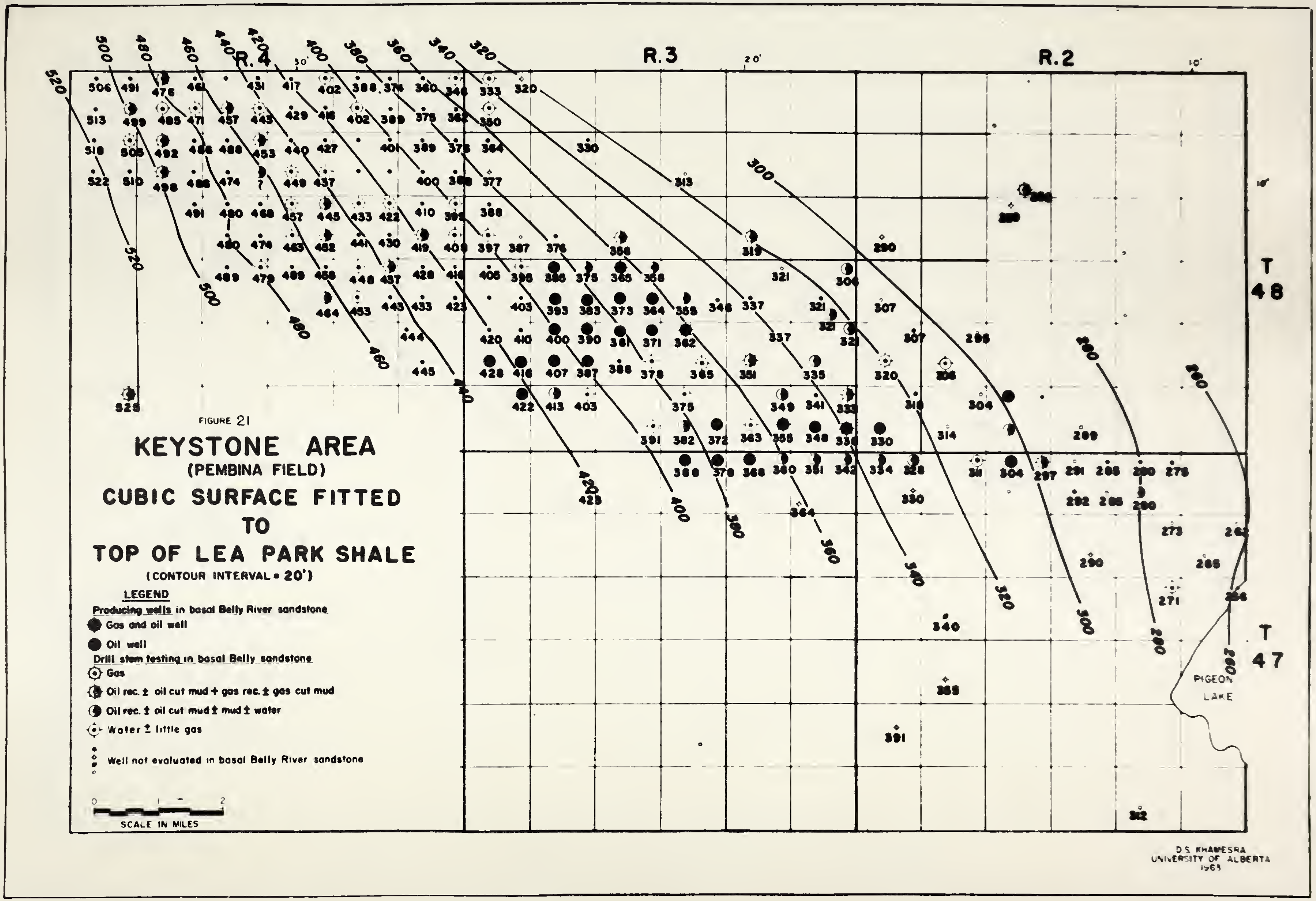
(PEMBINA FIELD)

DEVIATION FROM QUADRATIC SURFACE

ON TOP OF

LEA PARK SHALE

(CONTOUR INTERVAL = 10')


R.4
R.3
R.2
T 48
T 47
PIGEON LAKE
FIGURE 21
KEYSTONE AREA
(PEMBINA FIELD)
CUBIC SURFACE FITTED
TO
TOP OF LEA PARK SHALE
(CONTOUR INTERVAL = 20')
LEGEND
Producing wells in basal Belly River sandstone
Gas and oil well
Oil well
Drill stem testing in basal Belly sandstone
Gas
Oil rec. ± oil cut mud + gas rec. ± gas cut mud
Oil rec. ± oil cut mud ± mud ± water
Water ± little gas
Well not evaluated in basal Belly River sandstone
SCALE IN MILES
D.S. KHAMESRA
UNIVERSITY OF ALBERTA
1963

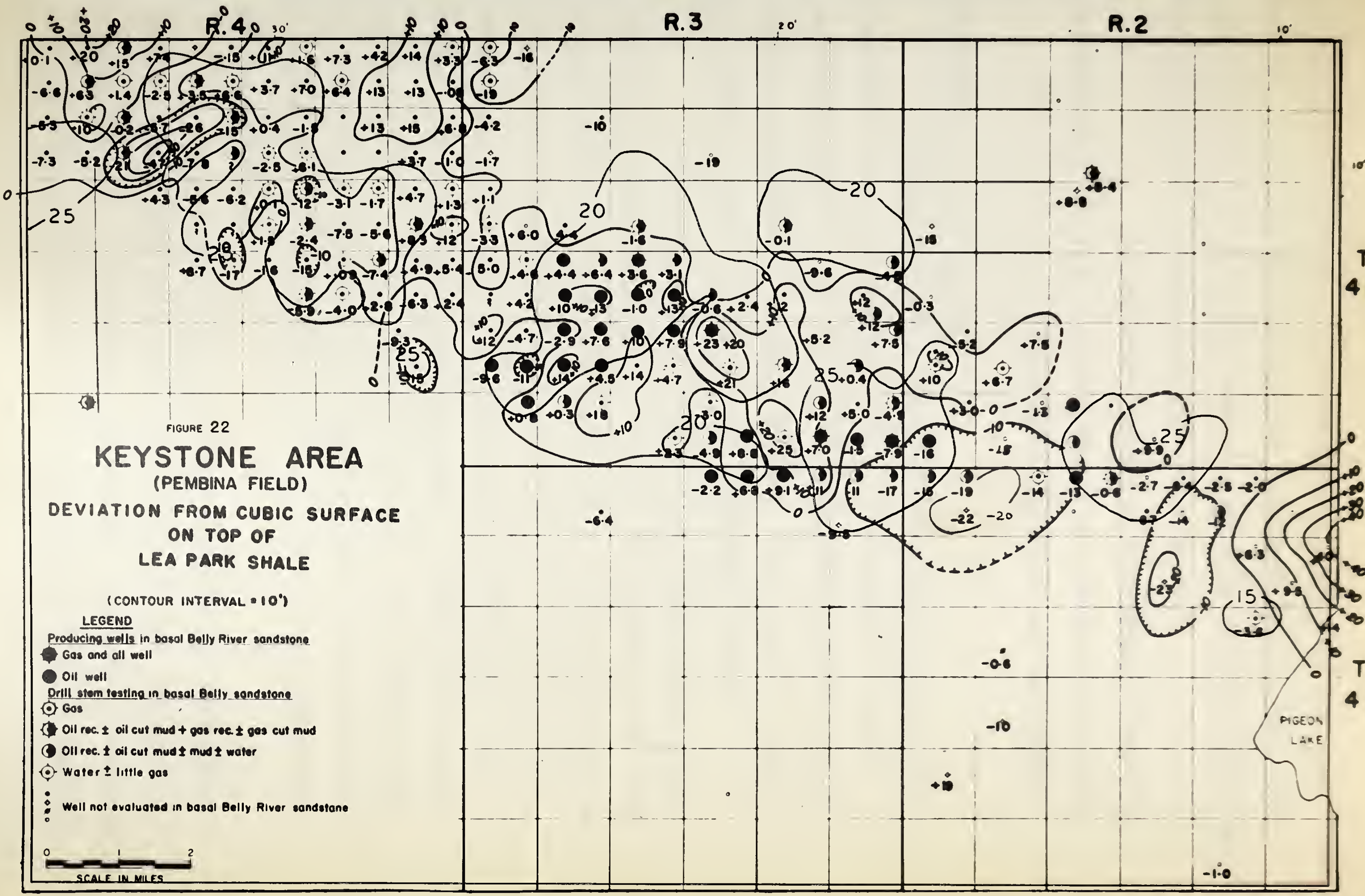
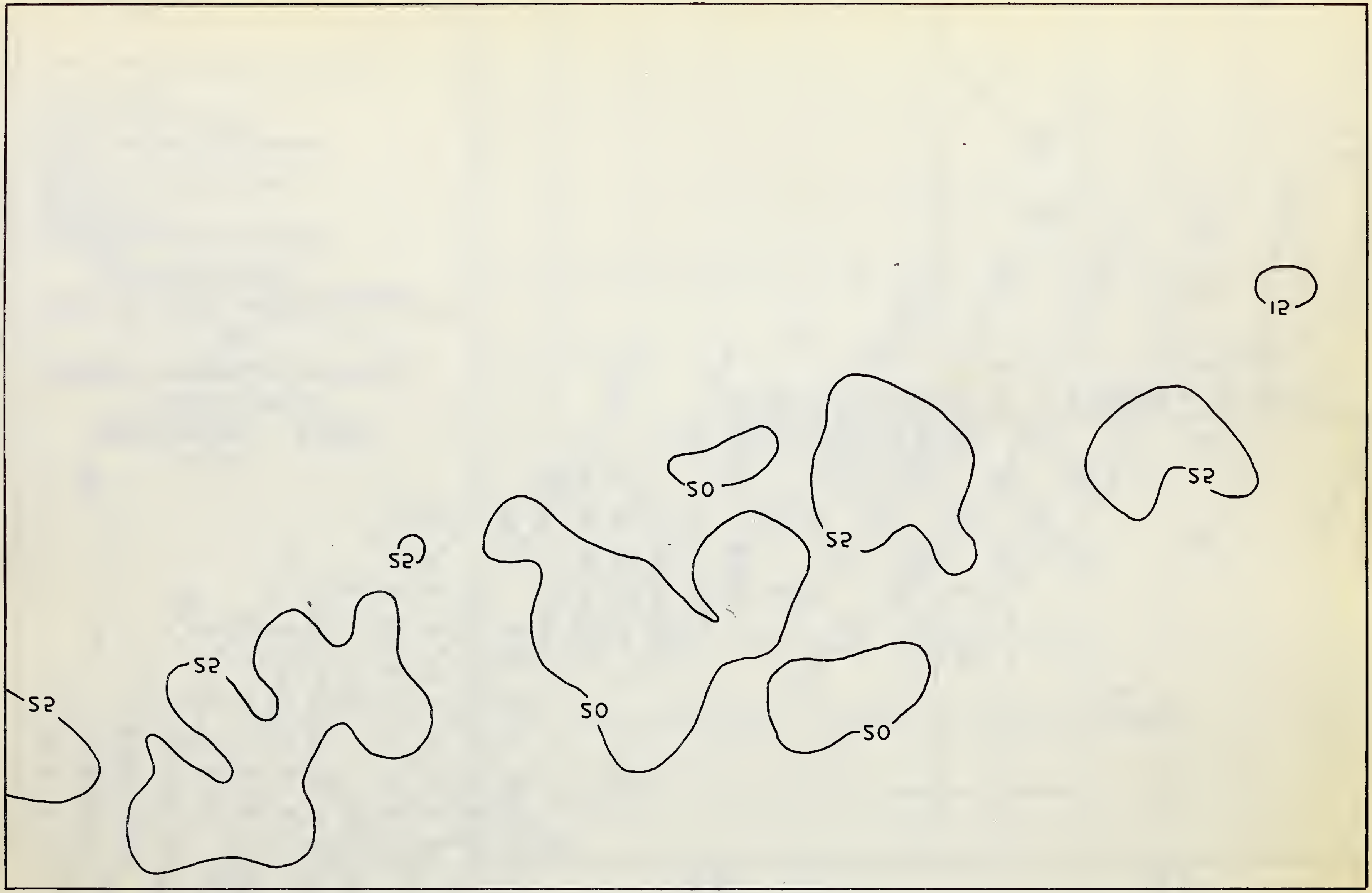


FIGURE An overlay of sand isoliths (See FIGURE 9)

FIGURE An overlay of sand isoliths (See FIGURE 9)



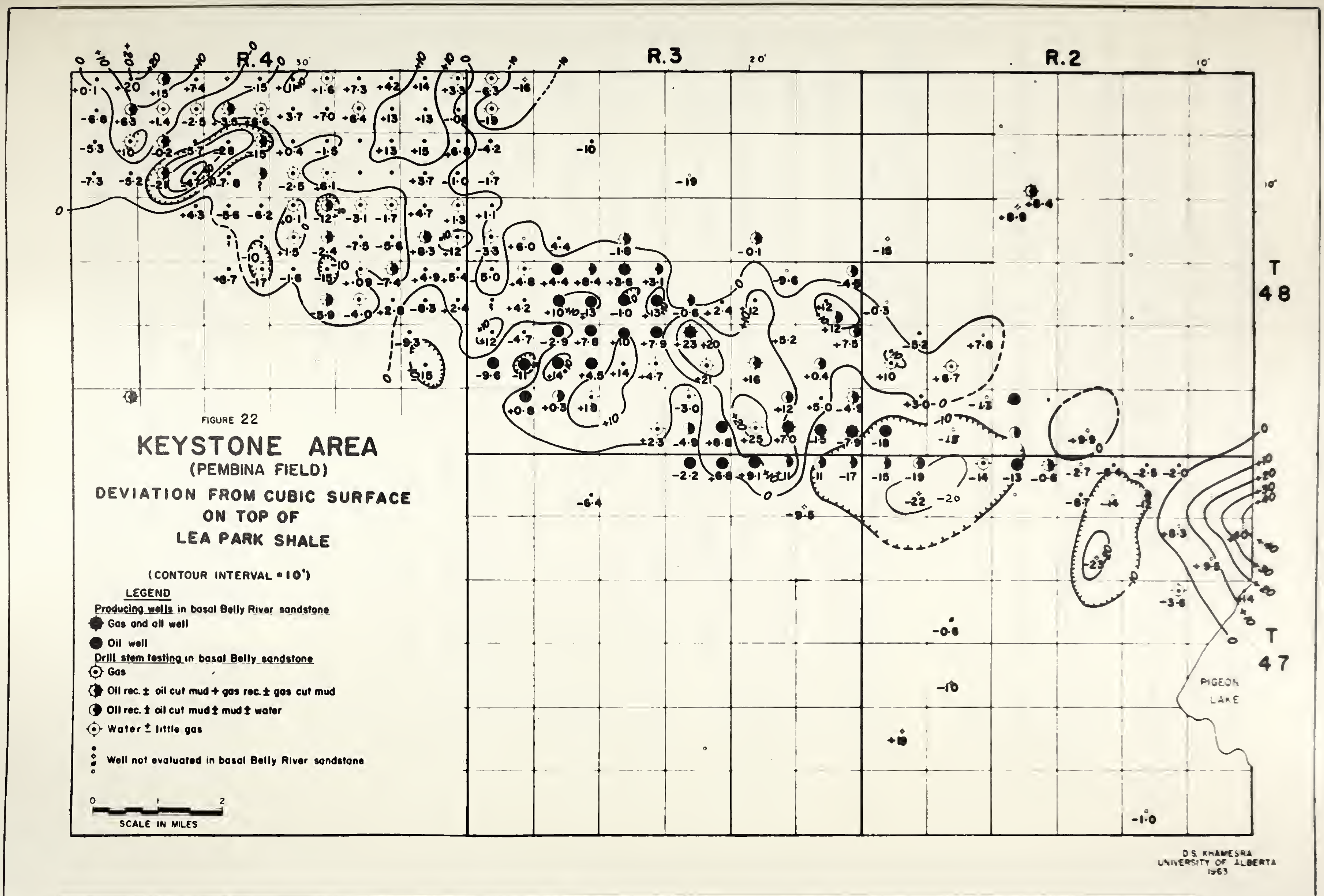


FIGURE 22

KEYSTONE AREA
(PEMBINA FIELD)
DEVIATION FROM CUBIC SURFACE
ON TOP OF
LEA PARK SHALE
(CONTOUR INTERVAL = 10')

roughly similar maps that may be interpreted in about the same way. However, it was felt that the analytic methods yielded a surface with less character than the graphic methods. Among the graphic methods, the one-ring method was smoother than the direct method.

In the present study, no relationship between the paleotopography and the sand accumulations was obtained and therefore it is difficult to say which method of analysis is more meaningful.

Discussion of Cross Sections

Stratigraphic cross sections along and across the shorter dimensions of the local sandstone bodies were prepared in order to study their geometry, i.e. shape, size, trend and their physical and genetic relationship to adjacent sediments, and to ascertain whether the different bodies occur at the same stratigraphic level.

The study was based solely on marker beds or datum planes which are considered to represent reliable time surfaces in the underlying Lea Park Shale in the area under study. It was assumed that the marker beds in the Lea Park Shale were horizontal or had negligible depositional slope when the overlying sandstone bodies were being formed. The bottom of the sandstone bodies are nearly flat when compared with datum markers in the Lea Park Shale. This indicates that no differential compaction in the intervening shale has occurred and the geometry of the sandstone bodies at the time of their deposition was truly restored.

Attempts were made to use time stratigraphic datum planes above the basal Belly River sandstone. Coal 2 and Coal 1 markers are slightly oblique to the markers in the Lea Park Shale and this obliqueness increases as the thickness of the intervening competent sandstone

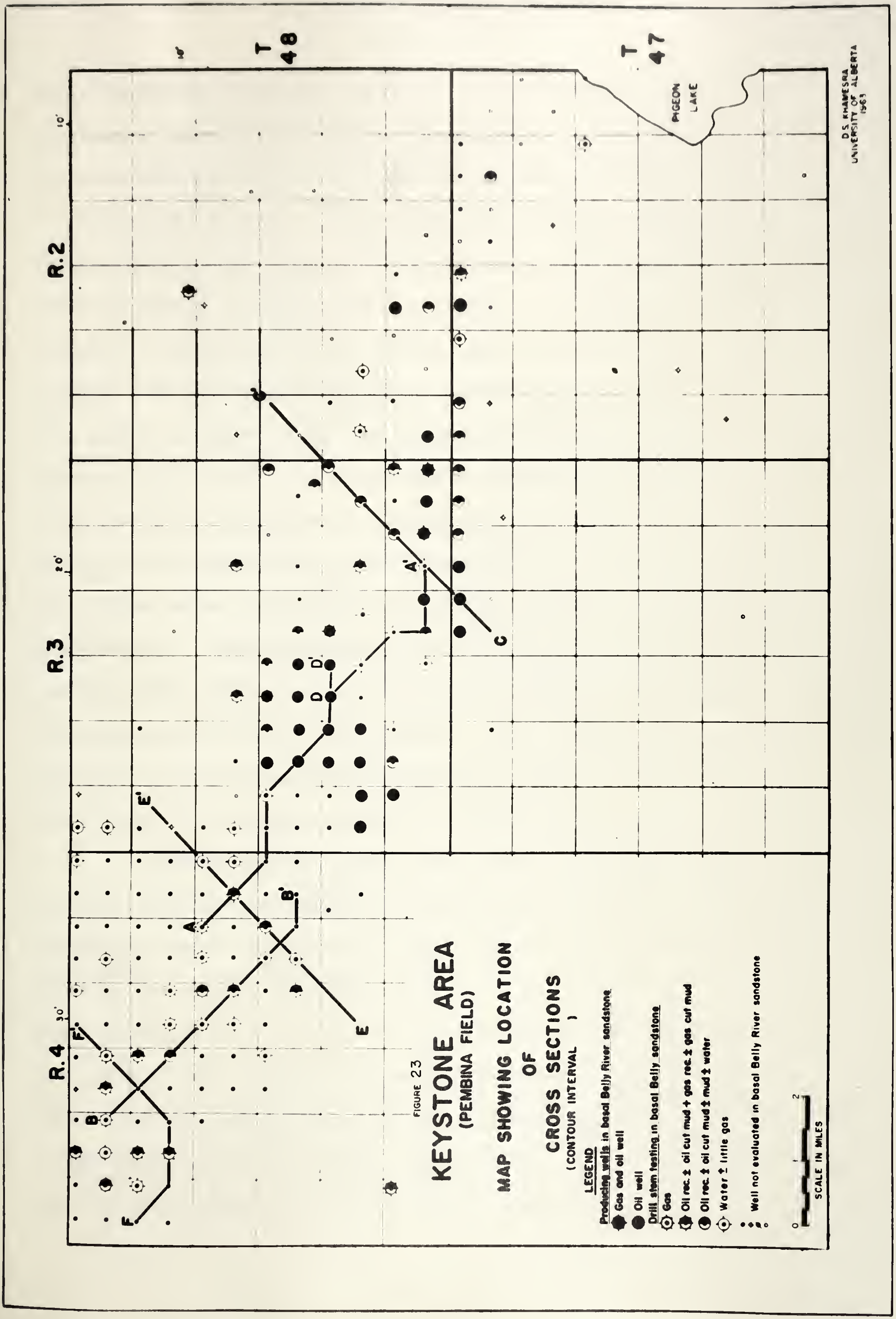
decreases. This suggests that the shale intervals between the coal markers and the sandstone bodies have been differentially compacted. The coal markers are therefore not considered to be reliable time stratigraphic markers for restoring the paleogeometry of the sandstone bodies. No cross sections with datum above the basal Belly River sandstone were therefore prepared.

It was thought that if the individual shale beds within the basal Belly River sandstone were carefully correlated from well to well and their manner of stratification and pinch out in relation to the sandstone bodies in space were known, it might help in understanding the configuration of the sandstone bodies and possibly their mode of origin. In order to achieve this, a detailed correlation of the individual shale beds within the basal Belly River sandstone was attempted using large scale logs (1" = 20'), wherever possible. It may be noted that the presence of shale beds was inferred mostly from the spontaneous potential log and all the "shales" identified may not be shales as discussed earlier. This is a serious limitation in carrying out such studies.

Structural cross sections were drawn along the same lines as stratigraphic cross sections (Figure 23) to examine the effect of present day structure as superimposed on the facies changes and their combined effect on the distribution of hydrocarbons within the individual sandstone bodies.

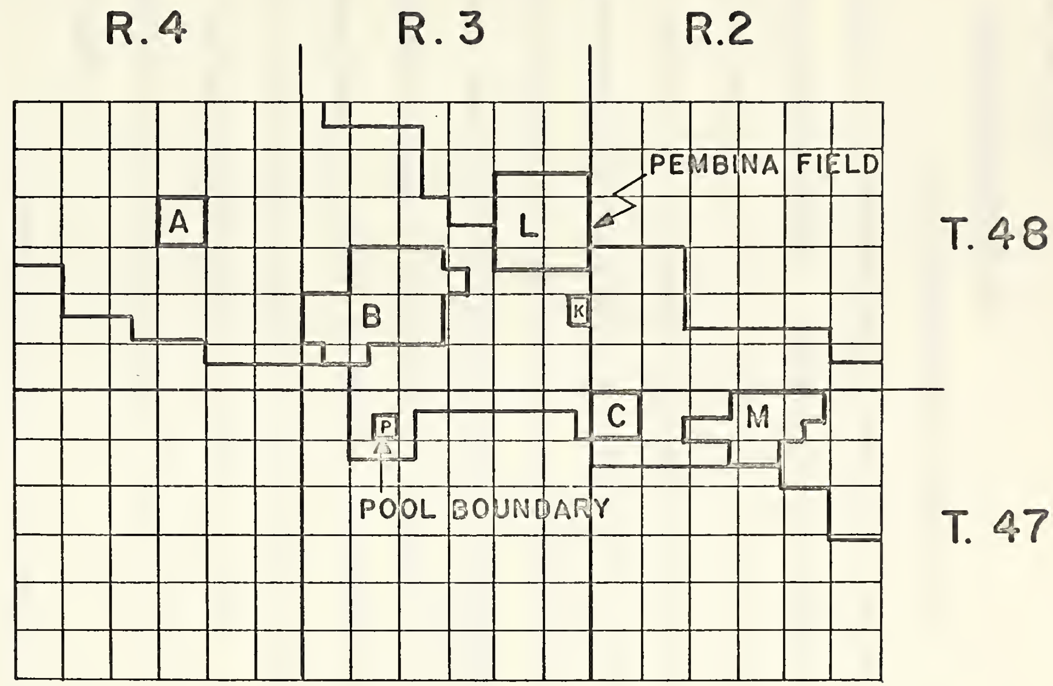
Cross Section A-A'

Cross section A-A' (Figure 24, in pocket) extends from the southeast part of body 8 through body 7 to body 4 in a southeasterly direction. Marker LP 3 in the Lea Park Shale was used as a datum. In wells where this marker was not penetrated, a floating


R.4
R.3
R.2
T 48
T 47
30'
20'
10'
PIGEON LAKE
A
A'
B
B'
C
C'
D
D'
E
E'
F
F'
FIGURE 23
KEYSTONE AREA
(PEMBINA FIELD)
MAP SHOWING LOCATION OF CROSS SECTIONS
(CONTOUR INTERVAL)
LEGEND
Producing wells in basal Belly River sandstone
Gas and oil well
Oil well
Drill stem testing in basal Belly sandstone
Gas
Oil rec. ± oil cut mud + gas rec. ± gas cut mud
Oil rec. ± oil cut mud ± mud ± water
Water ± little gas
Well not evaluated in basal Belly River sandstone
0
1
2
SCALE IN MILES
D S KHAMESRA
UNIVERSITY OF ALBERTA
1963

marker in the Lea Park Shale was used. The section shows three bodies separated by areas of poor sandstone development. Bodies are thickest in the central part and seem to shale out towards the margins. This is clearly seen in body 7. Body 4 terminates abruptly towards north against shale or sandy shale. Such pinchouts are perhaps responsible for the accumulation of hydrocarbons. The bodies are composite in nature, composed of sandstone and shale beds stacked one over the other. This may mean that the vertical and lateral growth of the bodies took place in a number of stages. The lower surfaces of the sandstone bodies approach very closely a plane that had a slight initial depositional slope towards the east whereas the top surfaces are convex upward with respect to the marker LP 4 in the Lea Park Shale. Towards the east, each of the bodies successively rises stratigraphically, though the rise is small. These three bodies constitute three separate stratigraphic traps in which hydrocarbons were accumulated and are separated from each other by areas of low porosity. The trap within body 7 was named by the Oil and Gas Conservation Board, Calgary, as the Keystone Belly River pool B and has produced oil (Figure 25).

Structural cross section A-A' shows the sandstone broken into three segments corresponding to three porosity pinchouts. Gas occurs in the structurally higher parts of body 8 while indications of oil were obtained from structurally lower parts. Body 7 is typical of the stratigraphic traps in the area. Oil occurs in the central thicker part whereas water wells lie on the marginal area. It may be noted that though the marginal water wells are structurally at the same level as the producing central ones they yielded water. This is interpreted as due to a facies change from thicker cleaner sandstones in the central



A is a gas pool, rest oil pools

FIGURE: 25 Pool boundaries in basal Belly River sandstone

(after Oil & Gas Conservation Board, Calgary)

part of the body to thinner shaly sandstones on the margins. In body 4, oil occurs at structurally lower level with respect to the marginal water wells to the east. This is again interpreted as a facies change from coarser cleaner sandstones in the central part to finer shaly sandstones towards the margins.

Cross Section B-B'

Cross section B-B' (Figure 26, in pocket) extends through body 8 in a southeasterly direction. The datum plane is marker LP 1 in the Lea Park Shale. Though the body appears to have a more or less regular thickness, it is suspected from the behavior of fluids in the wells tested that a permeability barrier may exist between the Cities Service Keystone 8-14 well and the Cities Service Keystone 8-22 well. Body 8 may therefore be broken into two separate smaller bodies, namely 8NW and 8SE. Body 8SE is slightly higher stratigraphically than body 8NW. The trap within a part of the body 8NW is named by the Oil and Gas Conservation Board, Calgary, as Keystone Belly River gas pool A (Figure 25). The lower surfaces of the smaller bodies approach very closely a plane sloping slightly towards the east. The top surfaces are rather smooth except for their minor convexity due to local thickening of the sandstones.

Along the section line, gas and oil occur in the structurally higher parts of body 8NW whereas body 8SE contains only water, although it is structurally higher than 8NW. This may be interpreted either as a facies change within a single body or as two different bodies separated by shale, with the latter interpretation being more likely.

Cross Section C-C'

Cross section C-C' (Figure 27, in pocket) extends through bodies 3 and 4 in a northeasterly direction. The datum is the top of the Colorado Group (First White Specks). In wells where this marker was not penetrated, a floating marker in the Lea Park Shale was used. As the spontaneous potential was not well developed against the sandstones in the wells along this section, correlation of individual shale beds was not possible and the detailed geometry of the sandstone bodies is somewhat obscure. The bottoms and tops of the bodies are almost flat. Body 3 seems to shale out in a northeasterly direction.

Oil occurs in the Whitehall Keystone 16-34 well which is structurally lower than the Whitehall Keystone 6-2 well which yielded water. This may again be interpreted as due either to a facies change within a single body or to different bodies separated by shale. The trap within a part of body 3 was named by the Oil and Gas Conservation Board, Calgary, as Keystone Belly River pool K and has produced oil.

Cross Section D-D'

Cross section D-D' (Figure 28, in pocket) uses marker LP 4 in the Lea Park Shale as a datum. It illustrates the rapid facies change on the central eastern flank of body 7 as it passes into shale. It may be noticed in the figure that when the bottom and top sandstone beds were being deposited in the Whitehall Keystone 14-9 well, mud and silt dominated in the Whitehall Keystone 16-9 well.

Cross Section E-E'

Cross section E-E' (Figure 29 in pocket) extends through body 8SE in a northeasterly direction. Marker LP 1 in the Lea

Park Shale is used as the datum. The body has a flat bottom and the top surface is slightly convex upward. It shales out towards the northeast. Oil and gas occur in the structurally higher parts of the trap with a gas cap in the highest part. The marginal Cities Service Keystone 16-24 well is dry, despite being structurally high, because of a poor porosity.

Cross Section F-F'

Cross section F-F' (Figure 30, in pocket) extends easterly and northeasterly through bodies 9 and 8NW. Marker LP 1 in the Lea Park Shale is used as a datum. The section shows two bodies separated by an area of poor sandstone development. Body 9 shows typical marginal thinning. Body 8 is inferred to shale out abruptly against shale or sandy shale towards its southwestern margin in contrast to its gradual shale out towards the northeast margin. It has a flat lower surface and shows a slight initial slope towards the northeast. Body 9 also has a flat bottom surface whereas the top surface is convex upward. The facies relationship in the bottom 20 feet of body 9 are quite clear. On any given depositional time plane within this interval, mud or silt was being deposited in the flank wells contemporaneously with sand deposition in the central well. After the lower 20 feet were deposited, mud and silt deposition continued to dominate the flank wells and is reflected by a large number of shale beds in these wells interfingering with sandstone in the central well. The base of body 8 seems to be about 20 feet stratigraphically higher than the base of body 9. This is indicated by the replacement of marker LP 4 in the Lea Park Shale by sandstone in body 9 in the Klinta Keystone 8-30 well.

Gas was found in body 8 in the higher part of the structure in one of the wells tested, and a show of gas and oil was encountered in body 9.

General Conclusions

The basal Belly River sandstone was deposited as a series of sandstone bodies in the Lea Park sea. Using the markers in the Lea Park Shale as datum planes, the flat bottoms and the upwardly convex tops are readily apparent. Markers Coal 2 and Coal 1 seem to be slightly draped over the basal Belly River sandstone due to differential compaction.

The isolith and sand-shale ratio maps of the basal Belly River sandstone do not indicate that the sandstone bodies are discontinuous areally. A sandstone-shale distribution of the type shown diagrammatically in Figure 31 is suggested to explain the relationship among sandstone bodies and the behavior of fluids in the wells tested. The sandstone bodies are thus separated by narrow belts of poor sandstone development or shale which do not allow free communication of fluids from one body to another.

The bodies usually have steep western slopes with abrupt facies change whereas the gentle eastern slopes shale out gradually. Shale beds are less frequent towards the western slopes and the sandstones are clean in contrast to the eastern slopes where shale beds interfinger frequently and the sandstones are shaly. Porosity pinch-outs towards the east give rise to water wells in structurally anomalous positions. It is expected that the western slopes of sandstone bodies should be more prospective than the eastern ones, because of the cleaner nature of the sandstones, with fewer intervening shales and resultant

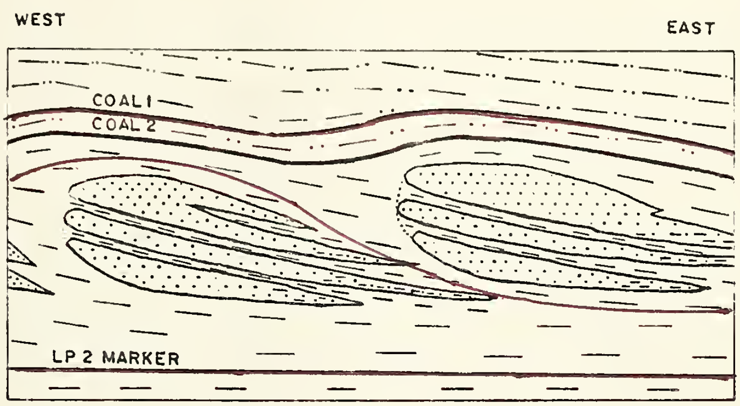


FIGURE 31 Diagram showing possible sandstone - shale distribution in basal Belly River sandstone

— *Time lines*

higher porosity and permeability.

Finally, the lobe of the basal Belly River sandstone extending southeasterly across the area studied is considered to be an off-lap sequence composed of individual sandstone bodies overlapping so that the body towards the east is stratigraphically higher than the preceding one.

CHAPTER THREE - SEDIMENTOLOGY AND SEDIMENTARY PETROGRAPHY

PARTICLE SIZE ANALYSIS

General Statement

The purpose of this part of the study was to aid in the determination of environment of deposition of the sediments from size analysis. An extensive literature is available describing various methods of sediment analysis in order to distinguish between sediments formed in different depositional environments.

Shepard and Moore (1955) defined fifteen different environments of deposition in the bays, on the barrier islands and on the open continental shelf based on : an examination under binocular microscope of the individual components (organic and inorganic) in the coarse fraction (greater than 1/10 mm) of the sediment; "pie" diagrams constructed of the percentages by weight of the individual components in the coarser fraction and the total amount of undifferentiated silt and clay; and triangle diagrams showing the sand, silt and clay content of the sediment.

Inman and Chamberlin (1955) made use of statistical measures to the size frequency distribution to distinguish among the various sediment types in a near shore environment.

Shepard (1960a) plotted the sand-silt-clay content of samples from various environments in the Mississippi delta on triangular diagrams. Each environment occupied a certain area within the triangle with some overlap from other environments. He also showed that the median grain size, the weight percent of sand and the weight percent of silt in the sediment when plotted and contoured show significant trends with respect to the margin of the Mississippi delta.

Shepard (1960b) pointed out that the large barrier islands on the northern Gulf Coast have at least four facies: beaches, dune belts, barrier flats or marshes, and inlets. Each of these have sediment characteristics which are usually distinctive.

Friedman (1962) showed that the standard deviation (sorting index) of a sand is a significant environment-sensitive textural attribute. A plot of skewness (third moment) against the standard deviation (sorting) for medium-to fine-and very fine-grained sands serves to distinguish beach sands from river sands.

Sabins (1963) considered the maximum grain size, median grain size and average sorting value as some of the important textural criteria in discriminating the bar sand facies from the beach sand facies, and the fore-bar facies from the back-bar facies.

Method of Analysis

Samples for mechanical analyses were selected from the wells where core recoveries were complete. Complete mechanical analyses were done on nine samples from three such wells. Mechanical analyses on four samples were repeated to test the reproducibility of the results. Of the nine samples selected, eight were from the basal Belly River sandstone and the remaining one was stratigraphically higher in the section, possibly from the Edmonton Formation. The pieces of cores selected were halved lengthwise and a portion of one-half used for the size analysis. The samples were initially broken into small chunks by a jaw crusher, and, if calcareous, were treated with 20 percent HCl and slightly warmed till all effervescence ceased, then washed and dried. Final disaggregation of all samples was done by using a wooden roller until all aggregates were broken. Care was taken to see that the

material being crushed was sieved often so that the finer material was not subjected to any more grinding than necessary. The crushed material was then sieved on a Ro-Tap sieve shaker for 10 minutes. The standard U.S. sieves of 35, 45, 60, 80, 120, 170 and 230 mesh were used.

Pipette analysis as described by Folk (1961) was used to separate silts (1/16 to 1/256 mm - 4 to 8 phi units) from clay (finer than 1/256 mm - 8 phi units). The pipette analyses were done on 5 to 15 grams fractions finer than 4 phi units. The fractions down to 8 phi units were withdrawn by a 25 c.c. pipette after intervals of time based on Stoke's law of settling velocities described by Krumbein and Pettijohn (1938, pp. 95-102).

Graphical presentation of size analysis data is given in Appendix F. The grain size is used as the abscissa and the cumulative weight percent as the ordinate. The size parameters calculated are shown in Table III.

Size Parameters Employed

Size parameters were obtained both by graphical and moment measures. In graphical measures, the size frequency curves were analyzed statistically and each sediment was described in terms of the median diameter, standard deviation, and skewness. These were computed from five percentile diameters obtained from the cumulative size frequency curve of the sediment and are defined as follows:

Median diameter (Md) $= \phi 50$

Graphic standard deviation (σG) (Inman, 1952) $= \dfrac{\phi 84 - \phi 16}{2}$

Inclusive graphic standard deviation (σI) (Folk and Ward, 1957) $= \dfrac{\phi 84 - \phi 16}{4} + \dfrac{\phi 95 - \phi 5}{6.6}$

Graphic skewness (SK_G) (Inman, 1952) $= \dfrac{\phi 16 + \phi 84 - 2\phi 50}{\phi 84 - \phi 16}$

where $\phi 5$, $\phi 16$, $\phi 50$, $\phi 84$, and $\phi 95$ are the diameters in phi units corresponding to the 5th, 16th, 50th, 84th, and 95th percentiles respectively of the cumulative curve.

In moment measures the mean, standard deviation and skewness were obtained for each sediment following the procedure described by Inman (1952, p.133).

Sorting and its Environmental Significance

The sorting or spread of the cumulative curve is measured by the coefficient of sorting (Trask,1932). The coefficient of sorting, So, is the square root of the ratio of the quartiles mm_{25}/mm_{75} where $mm_{25} > mm_{75}$. The quartiles are the size values in millimeters associated with the intersection of the 25th and 75th percentiles with the cumulative curve.

Inman (1952) noted that size frequency distribution curves approach a normal distribution and measures of sorting based on quartiles have no particular significance in the geometry of a normal curve. He therefore advocated the use of a sorting measure employing the 16th and 84th percentiles, instead of 25th and 75th percentiles used by Trask. Folk and Ward (1957) modified Inman's deviation measure by including in their parameter the 5th and 95th percentiles. Inman's and Folk and Ward's deviation measures describe more adequately the sorting characteristics of the sediment than does the coefficient of Trask. It may be mentioned, however, that some investigators (Schneiderhoehn,1953, Fuechtbauer,1959) have continued to uphold the usefulness of Trask's coefficient. From the foregoing discussion, it follows that the sorting coefficient and thus the sorting designation would vary depending upon the method used. In this study, however, all three types of

sorting coefficients are calculated and their corresponding sorting designations are shown in Table III. This table also summarizes and compares the sorting classifications of Trask Schneiderhoehn, Folk and Fuechtbauer.

A normal size distribution when plotted on probability paper gives a straight line. Many sediments show a grain size distribution on probability paper which is normal or close to normal. However, in the very fine grain-size ranges of many sandstones, there is a deviation from the straight line. Tanner (1958) has demonstrated that many sets of sedimentary data plot on probability paper as zigzag curves rather than straight lines. Friedman (1962) studied the grain-size distribution of 612 ancient and modern sandstone and sand samples. He plotted skewness (third moment) against kurtosis (fourth moment), which provides a more sensitive test of deviation from log normality than the straight-line probability plot, and showed that most of the samples do not follow a log normal function. Since the grain-size distributions of the majority of sandstones do not follow a log normal function, the question arises whether the sorting coefficients of Inman and Folk and Ward are more useful than parameters based on the 25th and 75th quartiles, such as Trask's sorting coefficient. For this reason, Friedman favored the moment measures to be adopted to determine the size parameters of a sediment.

Discussion of Results

The cumulative curves of three of the better sorted samples were plotted on log probability paper to examine if the size frequency distribution of the sediments was lognormal. It was found that the sediments show a departure from lognormality at both the coarse and

fine "tails" of the curve. The method of moments was therefore adopted to obtain the mean, standard deviation and skewness using logarithmic measures.

The sorting coefficients calculated by the moment method are equal to or greater than those calculated by graphic methods. The mean and the skewness calculated by the moment method are greater than those calculated by the graphic method. The tendency for higher values of size parameters obtained by moment measure is interpreted as due to the negative skewness of the cumulative curves, i.e., the curves are skewed to the right.

The use of standard deviation was made to help in understanding the environmental significance following the lines of Friedman. The sorting coefficients obtained could best be compared with the continental shelf sands below wave base from the genetic sorting classification adopted by Friedman (1962).

Skewness (third moment) and the standard deviation were plotted to distinguish between a beach and a river sand (Friedman,1962, Fig.10). The basal Belly River sandstones were found to belong to a river sand.

The grain-size analyses were plotted on sand-silt-clay triangular diagrams (Figure 32). All the analyses compare well with the deposits of the "nearshore gulf" environment as defined by Shepard and Moore (1955). However, no echinoids or glauconite which are normally expected in a "nearshore gulf" environment were found. Fragments of the pelecypod Inoceramus are often found in many of the upper Cretaceous beaches and barrier islands (Toots,1961). No such fragments were found in the samples studied.

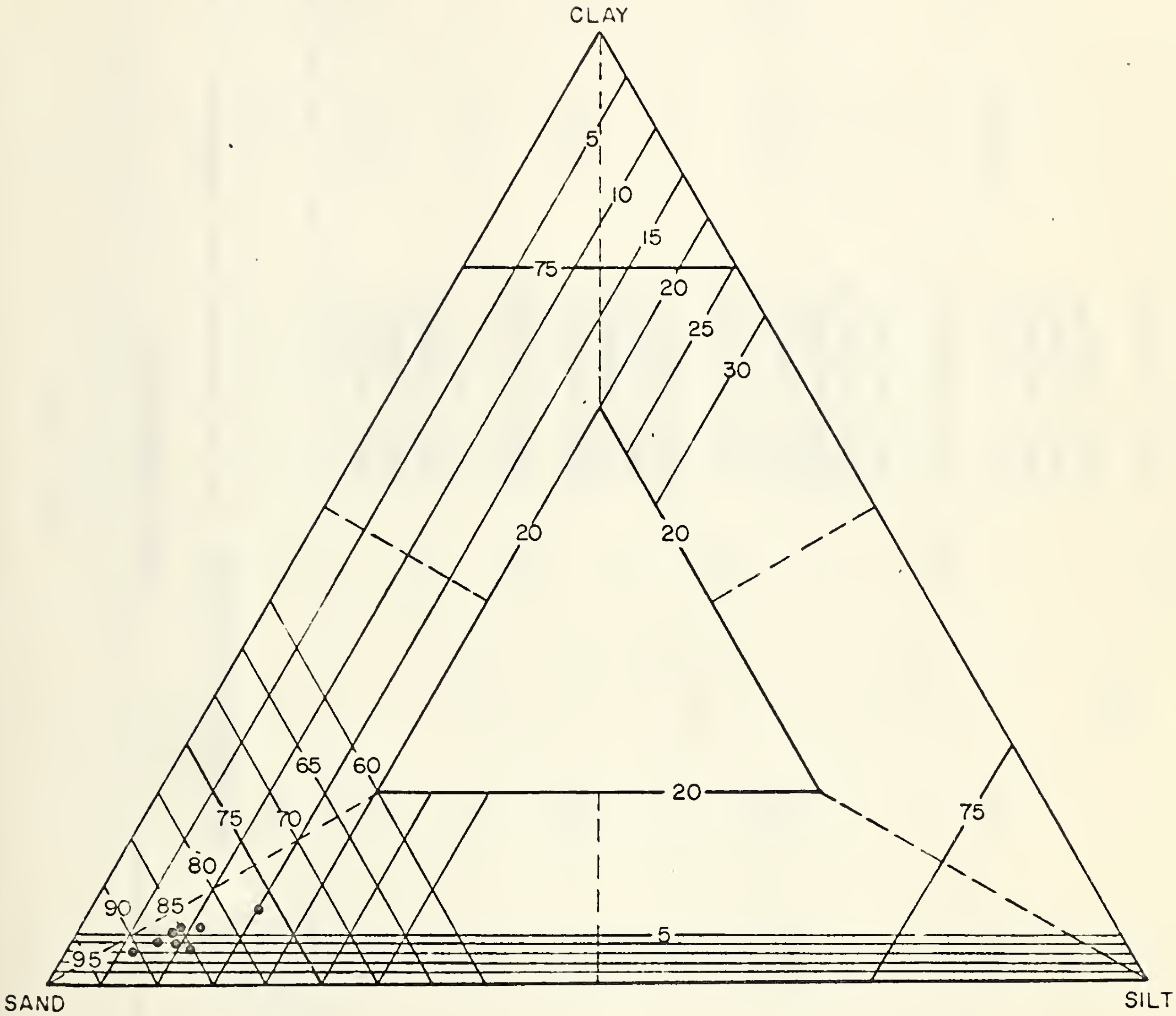


Fig.32 Sand-Silt-Clay percentage plotted on Sand-Silt-Clay Diagram.
(modified after Shepard and Moore, 1955,— fig. no. 14)

LEGEND

• Composition From Mechanical Analysis

TABLE III

			GRAPHIC MEASURES					MOMENT MEASURES		
Well location	Depth in Feet	Median diameter (Md) in phi units	Sorting coefficients So	Sorting coefficients σ_G	Sorting coefficients σ_I	Sorting designation	Skewness Sk_G	Mean	Standard Deviation	Skewness
6-3-48-3W5	3197.0	3.40	1.55			Well sorted[1]	-0.46	3.94		-1.37
						Mod. sorted[2]				
						Mod. sorted[3]				
						Mod. sorted[4]				
				1.80						
					1.90	Poorly sorted[5]			1.63	
	3202.5	2.72	1.58			Well sorted[1]	-0.54	3.41		-1.41
						Mod. sorted[2]				
						Mod. sorted[3]				
						Mod. sorted[4]				
				1.15						
					1.54	Poorly sorted[5]			1.74	
	3207.0	2.38	1.62			Well sorted[1]	-0.46	3.05		-1.82
						Mod. sorted[2]				
						Poorly sorted[3]				
						Mod. sorted[4]				
				1.17						
					1.64	Poorly sorted[5]			1.71	
	3214.5	2.50	1.52			Well sorted[1]	-0.43	3.06		-1.92
						Mod. sorted[2]				
						Mod. sorted[3]				
						Mod. sorted[4]				
				0.97						
					1.41	Poorly sorted[5]			1.61	

14-9-48-3W5	3061.5	2.30	1.55			Well sorted[1]	-0.38	2.81		-1.87
						Mod. sorted[2]				
						Mod. sorted[3]				
						Mod. sorted[4]				
				1.05						
					1.36	Poorly sorted[5]			1.55	
	3074.0	1.80	1.47			Well sorted[1]	-0.42	2.22		-2.11
						Well sorted[2]				
						Mod. sorted[3]				
						Mod. sorted[4]				
				1.02						
					1.10	Poorly sorted[5]			1.47	
	3082.0	2.00	1.58			Well sorted[1]	-0.39	2.55		-1.87
						Mod. sorted[2]				
						Mod. sorted[3]				
						Mod. sorted[4]				
				1.15						
					1.48	Poorly sorted[5]			1.71	
8-4-49-6W5	2425.0	1.90	1.37			Well sorted[1]	-0.47	2.47		-2.13
						Very well sorted[2]				
						Mod. sorted[3]				
						Well sorted[4]				
				0.95						
					1.44	Poorly sorted[5]			1.72	

1 Trask, 1932
2 Schneiderhoehn, 1953
3 Folk, 1954
4 Feuchtbauer, 1959
5 Folk and Ward, 1957

Summarizing, the basal Belly River sandstones are not as well sorted, and are more argillaceous than those of many modern beaches and barrier islands. The writer realizes that more analyses would be required to make a completely valid comparison.

Thin Section Study

The detailed petrography of the Belly River Formation has been described by Mellon (1961) and Lerbekmo (1962). The petrography of the basal Belly River sandstone is herein described only briefly.

The grain size varies from very fine sandstone to medium sandstone. The grade scale used was that published by the National Research Council (1947). The grains vary in roundness from angular to subrounded with the majority of sand grains being subangular to subrounded. Powers (1953) scale of roundness was used.

Essential components of sandstones are quartz, feldspars and rock fragments. The varietal minerals are carbonate, biotite, chlorite and muscovite.

Quartz is one of the most abundant detrital constituent of the rock. Most of the grains have an irregular shape and are markedly angular. Plutonic quartz or common quartz is most common. It is characterized by an irregular outline, straight to slightly undulose extinction and a moderate number of inclusions which are mostly scattered, or at times arranged in planes. Recrystallized metamorphic quartz occurs either as single individuals or composites made up of a mosaic of equidimentional grains having widely different optic orientations; it has a few inclusions. Stretched metamorphic composite quartz grains were observed which have crenulated or sutured boundaries between the sub-individual grains. Composite grains without

crenulated or sutured boundaries and showing strong undulatory extinction were also observed. Reworked quartz grains with quartz overgrowths were occasionally seen. A few quartz grains are fresh and clear with straight edges which might suggest them to be of volcanic origin.

Among the rock fragments, chert is the most abundant type. It is colorless to light brown in thin section. It commonly occurs as micro-crystalline quartz forming a pinpoint-birefringent aggregate of equidimentional grains, and at times as chalcedonic quartz forming sheaf-like bundles of radiating extremely thin fibres. The remaining rock fragments were treated as a single class for the sake of convenience and no attempt was made to break them further into sedimentary, metamorphic and volcanic types.

Feldspars are either fresh and colorless to slightly cloudy, or altered. No attempt was made to distinguish among the various feldspar species; however, Albite twinning is quite common indicative of plagioclase. Microcline was rarely seen.

Detrital carbonate occurs sporadically as single discrete grains. Biotite was observed in two varieties, pale brown and reddish-brown. In thin sections cut perpendicular to the bedding, it occurs as lath-like pleochroic grains, commonly distorted by compaction of the surrounding more rigid grains. Single grains of detrital chlorite, often distorted by compaction, are present. A light green micro-granular substance resembling chlorite in color and having lower firefrigence than glauconite may be chamosite. Distorted muscovite flakes are seen but are less common than chlorite.

Calcite is the usual cement and occurs as irregularly shaped patches filling the pore spaces between the detrital grains.

Calcite cement is clear and colorless and has crystallized as relatively large, optically contineous units, each crystal filling a cluster of adjacent pores. Calcite cement is also observed partly replacing the quartz, rock fragments and feldspar.

A slight silica overgrowth on few of the quartz grains was observed.

Classification of Sandstone

The classification scheme utilized here at the microscopic level is that proposed by Lerbekmo (1962) for the Belly River Formation. This classification embodies mainly the elements of schemes presented by Gilbert (1954), Travis (1955) and Crook (1960).

Gilbert's classification employs two diagrams of the QFR type. The first is the "wacke diagram" for arenites containing more than 10 percent detrital matrix and the second is the "arenite diagram" for arenites containing less than 10 percent matrix. The parameters of QFR diagrams are the percentages (on a matrix and cement-free basis) of quartz plus chert, feldspar, and rock fragments plus other labiles like chlorite or ferromagnesians etc. The shortcomings of the Gilbert classification are that the choice between the two diagrams depends on the arbitrary level of 10 percent and the restricted use of the term arenite.

A classification of marine sandstones combining compositional and primary structures was proposed by Packham (1954). Two groups of marine sandstones were recognized: graywacke - deposited by turbidity currents and characterized by graded bedding and sole markings; and arkose-quartoze sandstone suite - deposited by traction currents and characterized by current laminations. Each group has its

own MLQ (matrix, labile constituents, and quartz) diagram.

Some sandstone may not contain visible sedimentary structures or when data on sedimentary structures are not available, Crook (1960) proposed a nongenetic MLQ descriptive triangle and a subordinate QFR (quartz, rock fragments and feldspar) triangle to amplify the descriptive terminology of labile arenites. Arenite was used as a descriptive term for clastic material of sand size without genetic or mineralogical connotations. The term arenite was replaced by graywacke or sandstone when data on depositional environments were available. In this way, the Crook classification generates an objective descriptive term prior to application of genetic connotations of Packham's system.

Travis (1955) earlier proposed a QFR diagram which differs in certain respects with the Crook QFR diagram. Travis preferred to regard chert and quartzite as rock fragments and put them in rock fragments category instead of lumping them with quartz. Furthermore Travis nomenclature of rocks is much simpler. Travis suggested to use chert and quartzite as suffixes to the root name if they are present as a single dominant species, for example, chert lithic sandstone. Travis diagram does not contain graywacke term for he recommended to reserve greywacke only for those rocks which unquestionably qualify as such.

The classification followed differs only slightly from the Travis scheme of classification. Chert is placed in rock fragments category, but quartzite is lumped with quartz. Moreover the subdivisions of rocks within the triangle and their nomenclature, in places, is slightly modified (Figure 33).

Grain counts made on two of the slides and their plotting on the terniary diagram (Figure 33) indicate them to be lithic sandstones.

Heavy Accessory Minerals

The basal Belly River sandstone constitutes only a short

Whitehall Keystone 14-9 well
(Lsd.14, Sec.9, Twp.48, Rge.3 W5 Mer.)

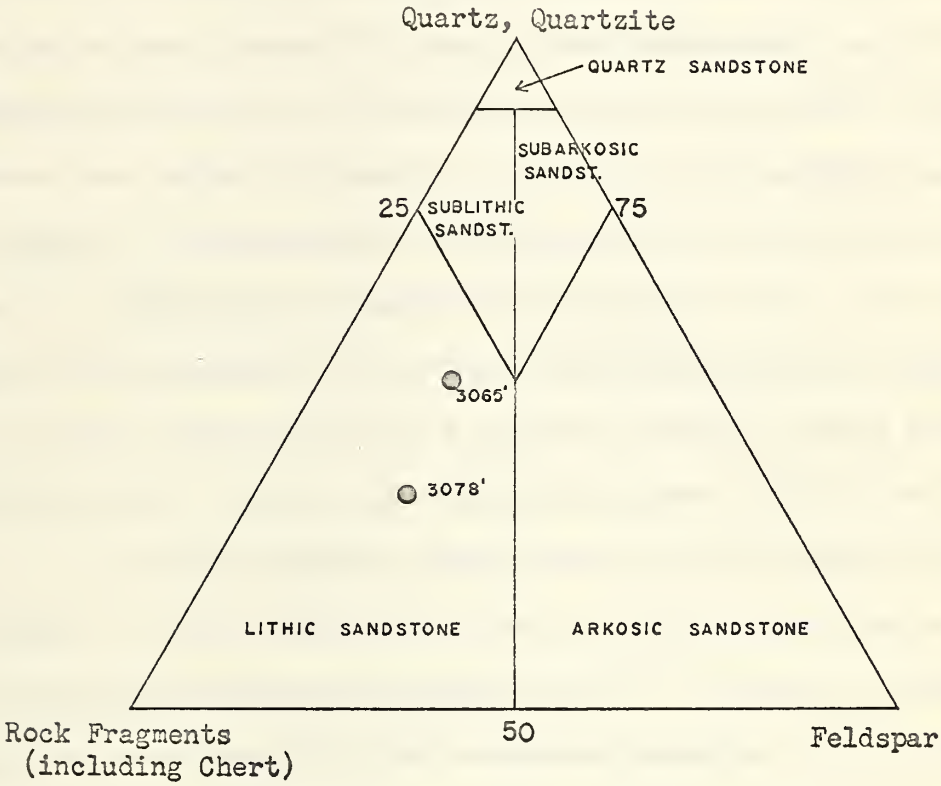


Figure 33 Compositional classification of basal Belly River sandstone
(After Lerbekmo, 1962)

stratigraphic interval at the base of the thick Belly River Formation. No attempt was therefore made to look for vertical variation in the heavy mineral suite. The heavy minerals present were studied to have some idea about the provenance of the detrital material.

Heavy minerals for study were obtained from the core in the Whitehall Keystone 14-9 well (Lsd.14, Sec.9, Twp.48, Rge.3 W5M.) at a depth of 3082 feet. The sample was disaggregated and dry sieved. The size fraction between 80 and 170 U.S. Standard mesh sieves was washed, dried and weighed. About 100 grams of this sample were separated in tetrabromoethane (S.G. 2.94 @ 20°C) in a separating funnel. The heavy minerals were washed with acetone to remove tetrabromoethane and dried and weighed. A representative fraction of heavy minerals was obtained by use of a microsplit and mounted in Aroclor ($n = 1.66$). The slide was examined microscopically using both reflected and polarized light. The heavy mineral count was made on a mechanical stage by making traverses across the slide. Both the non-opaque and opaque minerals were counted.

The heavy minerals make up less than 0.09 percent of the sandstone. A similar abundance of detrital heavy mineral was noted in the Belly River Formation by Lerbekmo (1962). The number of opaques plus siderite exceeded the other non-opaque minerals.

The relative abundance of non-opaque minerals present is shown below:

<u>List of non-opaque heavy accessory minerals in order of abundance</u>

Biotite
Carnet
Chlorite
Zircon
Apatite
Tourmaline

Heavy minerals present in minor quantities are rutile, andalusite, and possibly jarosite and spinel. Rare grains of calcite

(or dolomite) were noted; these grains were often found adhered to opaque minerals which caused them to sink through a heavier tetrabromoethane liquid.

Description of Non-opaque Heavy Accessory Minerals

Biotite - Occurs in two varieties, reddish-brown and pale brown; irregularly rounded, lacks pleochroism, inclusions with halos; alters to chlorite. The source may be regional metamorphic rocks for reddish-brown variety and biotite bearing igneous rocks for pale brown variety.

Garnet - Pale reddish purple, subangular to subrounded; fresh, showing conchoidal fracture and are probably first cycle; with or without inclusions, surface etched into a "mosaic" of pits. The pale reddish purple color of the garnet suggests it to be spessartite which would likely be of a metamorphic derivation.

Chlorite - Green to pale green, subangular to subrounded, occasionally micaceous, exibits compound polarization colors, sometimes in "ultra blue"; may be alteration of various ferromagnesian minerals.

Zircon - Light purple (hyacinth) variety, subangular to subrounded, euhedral, occasionally anomalously biaxial with small optic angle; a few grains contain rod-shaped inclusions, occasionally zoned. Hyacinth zircon is considered to be of Precambrian age and has likely survived several cycles of erosion and redeposition.

Apatite - Colorless, subangular to subrounded, inclusions arranged in rows. It is derived from acid igneous rocks and pegmatites.

Tourmaline - Predominating colors are brown in various shades, rarely green; euhedral to subangular and probably first cycle; inclusions common, occasionally well marked striations on the prismatic grains. The source may be igneous or metamorphic rocks.

Rutile - Deep reddish-brown, grains irregular, inclusions common. It is derived from acid igneous rocks and crystalline metamorphics.

Andalusite - Light pink, elongate prisms, marked pleochroism, inclusions common. It is derived from contact metamorphic zones in shaly material.

Clay Mineralogy

General Statement

Clays are important constituents of many reservoir sands. The study of clays is essential for an effective and efficient oil recovery program, as they determine to a large extent the porosity and permeability of a reservoir sand.

The clay size materials present in a reservoir sand are usually a mixture of clay minerals and non-clay minerals. The common clay minerals include kaolinite, illite, montmorillonite and chlorite. Non-clay minerals are usually fine quartz, feldspar, calcite, iron oxide and organic material. Non-clay minerals are usually proportionally less in amount and have much less effect in oil recovery problems due to their lowered or neutral reactivity with external fluids. Clay minerals, on the contrary, in contact with external fluids, such as water from infiltration of drilling fluid, lose their equilibrium with the reservoir brine resulting in base exchange,

ab.

swelling and deflocculation. Different clays behave differently depending upon their crystal structure and composition. Montmorillonite has the greatest base exchange capacity, swelling tendency and deflocculating property, whereas kaolinite has the least. Illite, degraded clay minerals, and mixed layer clays are intermediate. The effects on reduction of reservoir properties are in the same order.

The presence of clay minerals in a reservoir sand has also a decided effect on Mounce potential due to their base exchange property. It has been shown in the laboratory that different clay minerals affect potential to different magnitudes; montmorillonite having the greatest and kaolinite the least effect (Bacon, 1948). In the field, the order appears to be similar; montmorillonite, illite, and kaolinite affect potential in descending order of magnitude (Griffiths, 1952).

In the present study, an attempt was made to determine the type of clay minerals and non-clay minerals present in the basal Belly River sandstone, using the X-ray diffraction technique. The presence of clay minerals was determined with the help of oriented slides, the non-clay minerals by non-oriented slides. It may be mentioned, however, that most of the non-clay minerals can be identified on X-ray patterns obtained from the oriented slides.

Preparation of Slides

Oriented slide: The diffraction of X-rays by oriented samples was the basic technique employed in this study. A common sample preparation technique in clay mineralogy is to sediment the flaky clay mineral particles from an aqueous suspension onto a glass slide. In samples prepared this way, the "C" crystallographic axis of

the clay mineral, being essentially perpendicular to the largest surface of the flake, becomes preferentially oriented nearly perpendicular to the surface of the slide.

Preparation of the samples consisted of letting the clays settle in an aqueous suspension until a 50 ml aliquot of the suspension taken with a pipette from a given depth contained only particles less than 2μ. This aliquot was then put in a 150 ml beaker containing a frosted slide and allowed to stand until all material greater than $\frac{1}{2}\mu$ had sedimented onto the slide. Most of the remaining fluid was then pipetted off and the slides air dryed.

Non-oriented slide: The size fraction smaller than 4 phi units obtained from the size analysis was pressed into a rectangular groove (20mm x 10mm x 2mm) carved on an aluminium holder (35mm x 35mm) which was then exposed to the X-ray beam. Care was taken that the upper surface of the sample in the groove was flat.

Analytical Procedure

Slides were mounted on a standard Norelco diffractometer with geiger counter and subjected to Ni-filtered Cu-radiation at 35 KV and 15 MA. The goniometer scanned at $1^{\circ}2\theta$ per minute. To give best resolution rate meter settings were varied depending upon the diffraction intensity of the untreated, glycolated and heat treated samples. The geiger tube pick-up was operated at 1500 volts.

X-ray patterns were obtained for oriented slides both before and after ethylene glycol treatment in an evacuated container. The samples were later heated to 475°C for 12 hours in an electric furnace. No treatment was given to non-oriented slides.

Identification of Minerals

Clay Minerals: The untreated samples showed a strong 7 Å peak and subsequent integral series of 00ℓ reflections indicating the presence of kaolinite or chlorite.

All the untreated samples showed peaks at about 14.24 Å (up to 13.58 Å) indicating the probable presence of chlorite, montmorillonite, vermiculite or mixed layer clay. No shift in the 14.24 Å peak was obtained upon glycolating the sample, indicating a non-expandable mineral. Heat treatment of the sample increased the intensity of the 14.24 Å and almost destroyed the 7 Å peak. This indicated the presence of chlorite and probably that the 7 Å peak is partially due to kaolinite (Warshaw and Roy, 1961). Chlorite was also observed in thin sections.

Non-clay Minerals: All the samples gave strong 4.23 Å and 3.34 Å peaks, the latter being the larger. The 4.23 Å peak corresponds to a quartz spacing, indicating the presence of silt and clay size quartz. The 3.34 Å is a strong quartz reflection but is also the third order of the basal reflection for muscovite and illite. As no peak occured at 10 Å, which is the basal spacing of muscovite and illite, the possibility of these latter being present is eliminated. The 3.34 Å peak therefore belongs to quartz.

A strong 3.17 Å peak was obtained from all the samples. This may come from plagioclase feldspar. The presence of the latter is confirmed from the thin sections studied.

A peak of 3.01 Å corresponds to calcite. The calcite peak was present only if the sandstone had a calcareous cement.

Discussion of Results

The principal clay matrix present in the basal Belly River sandstone is kaolinite. It has the chemical composition $(OH)_8\ Al_4\ Si_4\ O_{10}$. Structurally, it consists of alternate sheets of silica tetrahedra and alumina units. The lattice does not expand because of the attraction of O and (OH) layers which are adjacent when kaolin layers are stacked one above the other. Because kaolinite is a non-swelling type clay with low base exchange capacity and low deflocculating tendency, it should not cause much clogging of the reservoir sands, when in contact with extraneous fluids. Also the Mounce potential should be least affected especially when it is present in a quantity less than 5 percent.

The calcite may reduce the spontaneous potential to a considerable extent inasmuch as it forms the cement and thereby reduces the permeability of the sandstone.

CHAPTER FOUR - MECHANICAL LOG ANALYSIS

TYPES OF MECHANICAL LOGS USED

Electrical Log

An electrical log consists of two basic types of recordings; on the left side of the log the spontaneous potential of the beds is whown whereas the right side is devoted to recordings of their electrical resistivities.

Spontaneous Potential Log

A spontaneous potential log is a record of naturally occuring potentials measured in a mud-filled bore hole. The presence of a natural potential implies that conductive fluids are present in the rocks penetrated by the hole.

The amplitude of the spontaneous potential of any given sandstone depends upon its nature and thickness and upon the contrast in chemical activity between the mud and the formation fluid. An infinitely thick clean sandstone gives a theoretical maximum value called the static spontaneous potential (SSP) for a given ratio of chemical activities. In a shaly sandstone, the spontaneous potential is reduced and termed the pseudostatic spontaneous potential (PSP) which is always less than static spontaneous potential.

In most cases the bed boundaries are located at the inflection points on the spontaneous potential curve. This fact provides a means of accurately determining the thickness of a bed from the spontaneous potential log.

It is possible to recognize on the spontaneous potential log a rather well defined base-line corresponding to shale

sections in the bore hole. Deflections from this base-line to the left are negative and to the right are positive.

Resistivity Log

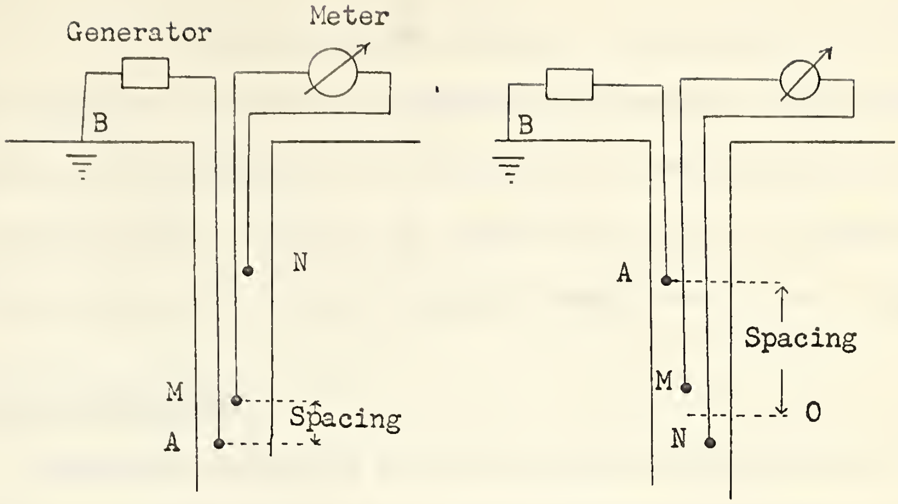
A resistivity log records the changes in the resistivity of the rocks and their contained fluids. The sharp contrast in electrical resistivity between rock types usually permits an electrical resistivity log to be interpreted uniquely in terms of lithology, porosity and water saturation of the beds penetrated.

Three resistivity measurements are recorded simultaneously. These are made by a short normal device (spacing AM = 16 inches), a long normal device (spacing AM = 64 inches) and a long lateral device (spacing AO = 18 feet 8 inches). The arrangement of electrodes in normal and lateral devices is shown in Figure 34.

A short normal curve is a measure of resistivity immediately adjacent to the bore and is affected by infiltration of drilling mud. In geological correlation work, the short normal is very useful as it responds to lithology and to tops and bottoms of formations showing sharp resistivity contrasts.

A long normal curve measures resistivity in an area more distant from the bore and is less affected by invasion by drilling fluids. It is not well adapted to the definition of bed boundaries.

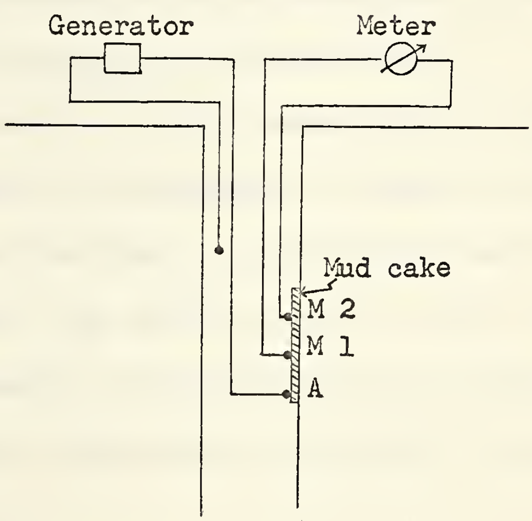
A common feature of normal curves is the reversal or "crater" which occurs when a hard, highly resistive streak of rock thinner than the electrode spacing is interbedded between rocks of lower resistivity. The long normal "craters" for thin resistive beds where the bed thickness is less than 64 inches. Instead of showing high resistivity, the recorded value is less at the center of the streak



A & B are current electrodes.

M & N are measuring electrodes.

Figure 34 Arrangement of electrodes in normal device (left) and lateral device (right)



A is current electrode.

M 1 and M 2 are measuring electrodes.

Figure 35 Arrangement of electrodes in microlog

and has a peak on either side giving the appearance of a "rim" around the crater.

A lateral curve responds to resistivity at a considerable distance from the bore, generally beyond the effect of mud penetration and contamination. It is useful for the location of thin, highly resistive beds, although the interpretation may be difficult in case of the presence of several successive beds close to each other.

Induction Electrical Log

Induction logging is a method wherein the conductivity (reciprocal of resistivity) of the beds is measured by means of induced currents without the aid of electrodes. The combination of an induction conductivity curve, a 16-inch normal curve and a spontaneous potential curve is called an induction-electrical log. An additional reciprocated curve of conductivity (or resistivity) is also recorded simultaneously making possible an easier comparison of the induction-electrical log with the conventional electrical log.

The main advantages of the induction log over the electrical log are its better ability to investigate thin beds, its greater radius of investigation and the fact that it can be run in empty holes or holes with oil base muds. The induction log is, however, not well suited for the determination of thin hard streaks whereas such hard streaks are usually quite conspicuous on the lateral curves.

Laterolog

The laterolog is a device for measuring resistivity wherein the current is forced to flow radially as a sheet of predetermined thickness, so that the measurement involves a portion of the rocks of limited vertical extent.

The main advantages of the laterolog over the electrical log are its sharper discrimination between different beds and more accurate definition of their boundaries, its use for logging of thin beds in a sequence of low to moderate resistivity where the drilling mud is very salty and for beds of high resistivity where any water base mud is used.

Microlog

A microlog is a resistivity log recorded with electrodes mounted at short distances from each other on an insulating pad which is pressed against the wall of the drill hole (Figure 35). It is capable of discriminating between very thin beds with different characteristics. It gives the exact location of the boundaries of permeable beds and makes possible the computation of the total thickness of potential pay zones.

The main principle of measurement is to apply three small size electrodes against the well bore one inch apart. The system A M_1M_2 provides a short lateral (or microinverse) device of spacing AO = 1.5 inches and the system A M_2 provides a small normal (or micro-normal) device of spacing A M_2 = 2 inches. The values read with these two different systems of electrodes are usually different, the difference being called the "separation".

In a porous zone, the micronormal is more affected by the invaded zone and less by the mud cake, so that the micronormal usually reads higher than the microinverse and the separation is called positive. A porous sandstone with high clay content may show a negative separation. In tight sections, the microlog readings are very high and show numerous sharp peaks and depressions; and the separation may be positive or negative. Shales are indicated by low

readings on microlog with a minimum of separation. However, in some instances, shales may give positive separation which may be mistaken for a permeable bed. It is then necessary to use spontaneous potential or gamma ray log to solve the ambiguity.

Microcaliper Log

A microcaliper log is a detailed record of the bore hole diameter to plus or minus 0.125 inches and is run simultaneously with the microlog. It is extremely useful because a decrease in hole diameter is likely to correspond to the presence of mud cake, indicating a permeable bed.

Sonic Log

Sonic logging fundamentally involves the recording of the time required for a sound wave to travel a short distance (usually one foot) through the rocks. Speed of sound in subsurface beds depends upon the elastic properties of the rock matrix, the porosity of the beds and their fluid content and pressure. The sonic log faithfully responds to changes in lithology in great detail and is perhaps the best log for correlation purposes.

Gamma Ray Log

The gamma ray log records the naturally occurring gamma radiation emitted by radioactive elements in the strata traversed. In most cases, a detectable variation of radioactive intensity occurs at each bed boundary. Generally sandstones are low in radioactivity, whereas shales, clays and siltstones have appreciably higher radiation activity. The gamma ray curve is thus directly applicable to identification and correlation of strata. By virtue of the penetrating power of gamma rays, gamma ray curve is obtainable regardless of the type or condition of the bore hole fluid.

In hard formations, where the spontaneous potential curve does not respond well to different lithologies the gamma ray log readily differentiates shales from the other rocks. When the salinity of the mud is very high, the spontaneous potential curve is reduced to a very smooth undulating and often practically straight line, and in such cases the gamma ray log provides the basis for differentiating sandstones from shales. Due to lag in response by the instrument, the survey can accurately resolve lithological changes only if the boundaries are about 2 feet or more apart.

Neutron Logging

A neutron curve is obtained by moving along the wall a source which emits energetic neutrons, together with a radiation detector spaced a fixed distance from the source. The detector may be either one which responds to gamma radiation (in which case the method is described as a neutron-gamma process) or one which is sensitive to neutrons (described as neutron-neutron n-n process). In either case, the results are nearly identical. The neutron log is a useful tool for the delineation of beds and for correlation in wells filled with water base mud, oil base mud or in empty holes, either open holes or cased.

The neutron log is essentially a record of hydrogen and clay content in the rocks. Both capture neutrons resulting in a slow counting rate and therefore it is necessary to use the gamma ray curve to locate porous zones. Ordinarily, sandstones show a higher counting rate compared to shales on neutron logs.

SPONTANEOUS POTENTIAL ANALYSIS

Theory of Measurement

The spontaneous potential curve or log is a record of natural occuring potential differences, between a surface electrode and an electrode in the column of conductive mud as this latter electrode is pulled up past different formations. As the surface electrode is stationary, its potential is constant, thus the spontaneous potential log is a record of the variations in the potential of the down-hole electrode. The down-hole potential variations are of two kinds: electrochemical and electrokinetic.

The electrochemical phenomena occur at the contacts between the drilling mud and the connate water in the pores of the permeable beds and the adjacent shales. The three media are separated by three boundaries across which three electromotive forces arise (Figure 36).

Two classes of reactions occur when the relatively fresh water of the mud in the well contacts the rock formations; one with the fluid content of the rock called the diffusion potential and the other with its solid framework called the Mounce potential.

Diffusion Potential

The mud-cake formed against the permeable bed acts as a semi-permeable membrane and a concentration gradient is established across it, if separated by salt solutions of different concentrations (Figure 36). Ions tend to diffuse from the more concentrated solution to the dilute solution thus the well fluid opposite a bed bearing salt water acquires negative charges with respect to the water in the bed, because Cl^- ions diffuse more rapidly than Na^+ ions. The resulting

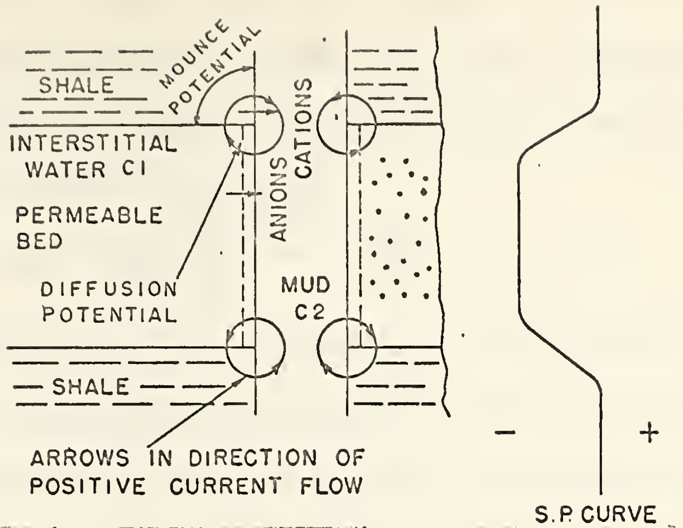


FIGURE 36 Schematic view of the potentials, current flow, ion movement and S.P. curve for a permeable bed containing a solution of concentration of C1. The bed is sandwiched between two shale beds and is penetrated by a borehole containing mud of concentration C2 (C1 C2)
(Modified after Wyllie, 1954)

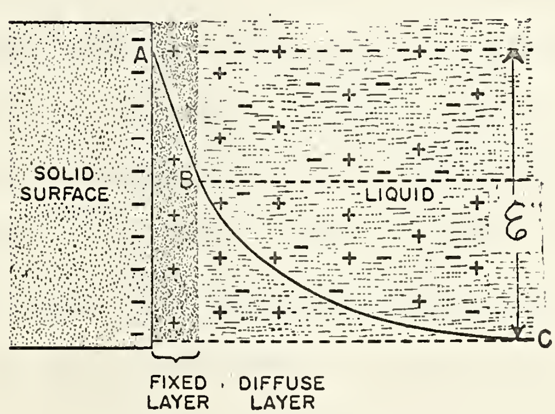


FIGURE 37 Schematic representation of the Mounce potential showing double layer (or Helmholtz double electric layer).
(Modified after Lynch, 1962)

diffusions potential in a natural system depends on the concentrations of the various ions present and their relative mobilities.

Assuming only Na^+ and Cl^- ions present and relatively dilute solutions, the magnitude of the diffusion potential Ed, in volts, may be evaluated by equation:

$$Ed = - \frac{V-U}{V+U} \frac{RT}{F} \log C1/C2 \quad \text{......(1)}$$

where C1 and C2 are the total concentrations of Na^+ and Cl^- ions present in the formation water and the well fluid respectively, V and U are respectively the mobilities of the cation and anion, R is the gas constant, T is the absolute termperature and F is Faraday's constant; substituting values of V = 0.000456 cm/sec @ 18^o C, U = 0.000676 cm/sec @ 18^o C, and $\frac{RT}{F}$ = 0.0575 @ 18^o C into equation (1) we get:

$$Ed = -11.2 \log C1/C2 \quad \text{......(2)}$$

Mounce Potential

When a shale is brought into contact with fresh water, such as drilling mud, the negatively charged chlorine ions remain preferentially absorbed by the clay and the positively charged sodium ions enter into solution. However, some of the Na^+ ions are electrostatically attracted by the negatively charged clay particles and remain in the vicinity of the clay, forming a fixed layer or Helmholtz double electric layer while others wander at near liberty away from the clay particles forming a movable layer (Figure 37). Thus the potential difference between the clay particle and any point within the water solution depends on the distance between them, and increases with increasing distance (Figure 37).

The maximum potential difference is called the thermodynamic potential $\mathcal{E}$ of the substance and is given in volts by

the Nernst formula:

$$\mathcal{E} = -\frac{RT}{nF} \ln a1/a2 \qquad ......(3)$$

where a1 and a2 are the activities of the sodium chloride solutions in the movable and fixed layers respectively, and ln is the natural logarithm (base e) = 2.303 (log 10).

At temperature 18°C, for NaCl solution, equation (3) can be written as $E = -57.5 \log C1/C2 \qquad ......(4)$

(The activity ratio is replaced by concentration ratio in equation (3) assuming dilute solutions).

As the spontaneous potential log measures the sum of the diffusion and shale potentials placed in series relative to the shale base-line, deflection observed would essentially be obtained by adding the equations (2) and (4). Hence

$$SPmv = -(11.2 + 57.5) \log C1/C2 \quad .....(5)$$

The concentrations C1 and C2 may be replaced, as a first approximation, by the electrical conductivities of the two solutions. Conductivity is the reciprocal of resistivity and hence equation (5) may be written as:

$$SPmv = -(11.2 + 57.5) \log \frac{R2}{R1} \qquad ......(6)$$

where R2 is the resistivity of the mud filtrate, designated conventionally as Rmf and R2 is the resistivity of the formation water, designated conventionally as Rw. Thus the equation (5) can be written as:

$$SPmv = -68.7 \log \frac{Rmf}{Rw} \qquad ......(6)$$

The coefficient 68.7 is the spontaneous potential lithologic factor (K) at 18°C for a geologic sequence of clean sands and shales and depends upon temperature. In the present study, the formation temperature of the basal Belly River sandstone is taken as approximately 96°F or 35.5°C. The value of K corresponding to this temperature is equal to 73 (Appendix G).

The electrokinetic phenomena are caused by the infiltration of the mud filtrate into the permeable beds. This infiltration causes an electromotive force or electrokinetic potential to appear primarily where the pressure differential is at a maximum i.e. across the mud-cake produced from the mud in the bore hole against the permeable bed. The electrokinetic potential depends mainly on the differential pressure between mud column and formation, mud filtrate viscosity and resistivity (Perrin 1904). In most cases, electrokinetic potential effects can be neglected, at least to a first approximation, and the entire spontaneous potential may be considered only a manifestation of the electrochemical potential (Mounce and Rust, 1944; Dickey, 1944, Wyllie, 1954 p. 26). The electrokinetic potential was therefore neglected in the present study.

Modifying Factors

The shape and amplitude of the deflection of the spontaneous potential curve opposite any given bed may be influenced by the following factors (Doll, 1948):

1. The total electromotive force involved;
2. the resistivity of the bed, of the surrounding formations and of the mud;
3. the diameter of the drill hole;
4. the depth of penetration of the mud filtrate into the permeable bed and
5. the thickness of the bed.

As shown above, the electromotive force depends on the salinity of the fluid in the permeable bed, on the nature of the impervious beds with which it is in contact and on the nature of the mud.

In the area under study, wells were drilled using a wide variety of drilling muds. These ranged from water-base muds (Rmf = 1.7 to 8.4 ohm-m @ 64°F), oil-emulsion muds (Rmf = 1.9 to 10.1 ohm-m @ 64°F) to "calcium chloride-starch" muds (Rmf = 0.3 to 0.7 ohm-m @ 64°F). Variations in the nature of the mud has caused wide fluctuations in the spontaneous potential response. Spontaneous potential is poorly developed in those wells where "calcium chloride-starch" muds were used.

A reduction in the amplitude of spontaneous potential is caused by an increase in the diameter of the hole, by an increase in resistivity of the bed, and by an increase in depth of penetration of the mud filtrate into the bed. In the present study, such effects are considered to be small or at least constant, and are ignored.

Whenever the thickness of the bed is less than twice the diameter of the hole, the amplitude of spontaneous potential decreases from the theoretical maximum and decreases very rapidly when the thickness falls below one half the diameter of the hole (Doll, 1948). The average hole diameter was about 8 inches in this study and thus spontaneous potential correction would be needed only for beds which are less than about 1.5 feet thick.

<u>Determination of Formation Water Resistivity (Rw) from the Static Self Potential (SSP) : Clean Sandstones</u>

A knowledge of formation water resistivity is basic to the interpretation of electric logs. Formation water resistivity (Rw) may be obtained by quantitative analysis of the spontaneous potential curve, however, it is advisable, whenever possible, to ascertain its value by other independant means. Various methods employed in this report are discussed on pp. 114 .

The static spontaneous potential (SSP) is related to the

activity of the formation water and of the mud filtrate, such that

$$SSP = -K \log aw/a_{mf} \qquad \ldots\ldots(6)$$

where aw and a_{mf} are the activity of connate water and mud filtrate respectively, and K is the spontaneous potential lithologic factor.

To a first approximation activity is equal to concentration and this in turn is essentially equal to the reciprocal of the electrical resistivity, thus equation (6) may be written

$$SSP = -K \log \ Rmf/(Rw)e \qquad \ldots\ldots(7)$$

where (Rw)e is the equivalent resistivity of the formation water and except for very saline or fresh water is nearly equal to Rw, the true formation water resistivity.

Of the wells studied, the spontaneous potential is best developed in the Med. Keystone 14-36 well (Lsd. 14, Sec. 36, Twp. 48, Rge. 4 W5 Mer.) and it perhaps contains the cleanest sandstone in the area. It was therefore chosen for the determination of Rw from the spontaneous potential curve. The following values from this well and equation (7) yielded Rw = 0.24 ohm-m @ 64^{o}F.

S.P. = -96 mv

K = 73 @ formation temperature 96^{o}F

Rmf = 4.7 ohm m @ 64^{o}F

Schlumberger nomograms A10 and A12 were used to solve equation (7).

Determination of Formation Water Resistivity (Rw) : Shaly Sandstones

In shaly sands, the spontaneous potential deflection is called pseudostaic spontaneous potential (PSP) which is smaller than the static self potential for the values of Rmf and Rw. In other words, equations (6) and (7), if applied to shaly sandstones, will give an

erroneously large value of Rw which is called the apparent water resistivity (Rwa).

As an example, consider the Texaco Sacony War. 2-28 well (Lsd. 2 Sec. 28, Twp. 48, Rge. 2 W5 Mer.) in which the formation water resistivity is directly known to be 0.33 ohm-m @ 77°F (Appendix I) from fluid recovered during drill-stem testing. Now, if equations (6) and (7) which hold true only for clean sands, are applied to determine Rw, values of 0.7 and 0.6 ohm-m @ 77°F are obtained. These latter values are called apparent water resistivities (Rwa).

Determination of 'Shaliness'

'Shaliness' is a measure of the content of disseminated clay material in a bed. It is calculated from the recorded spontaneous potential, the interstitial water and mud filtrate resistivities, and the formation temperature (Slack and Otte, 1960).

The quantitative treatment of electric log data for shaly sandstones used in this study is basically that proposed by de Witte (1955). From theoretical considerations de Witte showed that, in the case of a water-bearing shaly sandstone, the static electrochemical component of the spontaneous potential is given by

$$SSP = -K \log \frac{m_r + 2.15\, m_w}{m_r + 2.15\, m_{mf}}$$

where

m_r = concentration of fixed negative charges (ions) in the internal solution of the rock network in gram equivalents per liter of solution.

m_w = molality of the formation water in molecular weights of salt per liter of solvent (obtainable from Rw).

m_{mf} = molality of the mud filtrate in molecular weights of salt per liter of solvent (obtainable from Rmf).

Because the fixed negative charges in the internal solution are largely due to the presence of disseminated clay particles in the rock pores, m_r can be considered a measure of the amount of clay, the 'shaliness' of the bed.

In an oil-bearing bed, the concentration of fixed negative charges is increased by a factor 1/Sw, where Sw is the formation water saturation expressed as a fraction of the available pore space. For such a bed, and where the internal solution in the uninvaded portion is in equilibrium with the invading mud filtrate, de Witte showed that the spontaneous potential is given by

$$SSP = -K \log \frac{m_r/Sw + 2.15\, m_w}{m_r/Sw + 2.15\, m_{mf}} \quad \ldots\ldots(8)$$

The above equation contains two unknowns, m_r and Sw. Because it is difficult to obtain independent values for Sw, the ratio m_r/Sw, is called m_s, the 'shaliness' of the formation. A limitation of this procedure is that variations in Sw cause variation in the ratio of m_r/Sw which may then be incorrectly interpreted as variations in shaliness.

The value of m_s was calculated for each well in the area of study using equation (8). Variations in m_s are shown on Figure 13. The following example illustrates the method used.

<u>Sample calculation</u>

Data necessary to determine shaliness are as follows:

Well: Med.Keystone 14-36 (Lsd.14,Sec.36,Twp.48,Rge.4 W5M.)

K = 73 @ formation temperature 96°F

S.P. = -96 mv

Rw = 0.23 @ 64°F

Rmf = 4.7 @ 64°F

m_w is the molality of the interstitial water which is obtained from the resistivity of the formation water Rw as follows:

$$m_w = \frac{\text{ppm NaCl}}{58\text{x}1000} = \frac{32,000}{58,000} = 0.57 \text{ mol wts./lit.solvent}$$

(Schlumberger Chart A6 for the method of obtaining ppm from Rw)

Similarly

$$m_{mf} = \frac{\text{ppm NaCl}}{58\text{x}1,000} = \frac{1,250}{58,000} = 0.028 \text{ mol wts./lit.solvent}$$

Equation (8) is now solved for m_s :

$$\text{antilog}\ \frac{96}{73} = \frac{m_s+2.15\ (0.57)}{m_s+2.15\ (0.028)}$$

$$\text{or} \quad 20.6 = \frac{m_s+1.22}{m_s+0.06}$$

$$\text{or} \quad 20.6\ (m_s - 0.06) = m_s - 1.22$$

or $m_s \approx 0$ i.e. the 'shaliness' is nearly zero or the sandstone is clean.

Routine calculations for m_s were made using an I.B.M. 1620 computer. For programming see Appendix N.

Spontaneous Potential Reduction Factor (α)

A convenient semi-quantitative approximation to the 'shaliness' of a bed is the spontaneous potential reduction factor (α) which is the ratio of observed spontaneous potential to a theoretical maximum for the bed

The reduction factor α = PSP/SSP (Le Roy and Haun, 1958, p.285) is a convenient factor which can be calculated if SSP is known.

It ranges from 1 for clean sandstone to zero for shale. Values of α were computed for the wells in the present study and a contour map was prepared (Figure 11).

SPONTANEOUS POTENTIAL AND MINERAL COMPOSITION

General Statement

The investigation was intended to study the effect of mineral composition on the spontaneous potential curve on a semi-quantitative basis, using X-ray diffraction techniques. For this purpose, the matrix of 11 sandstone samples from the Imperial Canadian Superior Berrymoor 8-4C well (Lsd. 8, Sec. 4, Twp. 49, Rge. 6 W5 Mer.) was studied. The results obtained, though not conclusive, render some suggestions as to how such a method of study can be improved.

There is some difference of opinion regarding the interpretation of the spontaneous potential curve; some experts believing that the potential difference measured is essentially due to physico-chemical factors in the fluids of the bore hole and formation whereas others believe that the formation itself exerts the main control (Griffiths, 1952). No attempt seems to have been made to investigate formation composition i.e. mineral composition in sufficient detail to resolve the controversy.

A logarithmic relationship of spontaneous potential to the kaolinite content of a sand was established by Bacon (1948) using artificially prepared mixtures of sand and kaolinite. It was shown that when an unconsolidated sand contained more than 10 percent kaolinite, the potential for the sand was almost the same as from the clay mineral itself and that as little as 1 percent kaolinite would reduce the observed maximum potential to one half.

Griffiths (1952) plotted the clay content (weight percentage of material less than 3.9 microns) against the spontaneous potential in millivolts on Miocene sediments of southern Trinidad. A hyperbolic relationship of the form $Y = a/X + b X$ was observed, where Y is expressed in millivolts and X represents percent of clay. It was shown that a range from 3 to 30 percent of clay was sufficient to account for the minimum to maximum range of self potential measured.

Winsauer et al. (1952) related the Mounce potential of samples of sandstones to their clay contents and observed a trend of increasing positive potential with increasing clay content.

Method of Study

The Imperial Canadian Superior Berrymoor 8-4C well (Lsd. 8, Sec. 4, Twp. 49, Rge. 6 W5 Mer.) was chosen for study as it had a complete core recovery. Eleven samples of coarse to fine grained sandstone were picked (see Appendix E, pp. xxxiii). Shaly siltstone, shale with siltstone lenses and shale were omitted as no spontaneous potential response was observed against these rock types.

The size fraction smaller than 4 phi units (= 0.0625 mm) was considered as matrix of the sandstone, and the percentage of this matrix in the bulk sample (designated as % matrix) was calculated. It was assumed that the matrix largely controls the porosity and permeability in the sandstone and, in turn, the spontaneous potential response.

To determine the relative abundance of minerals present in the matrix recovered from the sandstone, X-ray diffraction technique was used. The matrix was transferred to a mount which consisted of an aluminum holder with a rectangular cavity grooved into it. A sample of matrix was placed in the cavity and the upper surface was pressed flat

with a small spatula. The mount thus obtained was carefully clamped into the X-ray unit for analysis.

The relative peak heights of the most intense reflection of various minerals on the diffraction curve was used as a semi-quantitative measure of their relative abundance. The peaks at 3.34 Å, 7 Å, 3.17 Å, and 3.01 Å corresponding to quartz, kaolinite, plagioclase feldspar and calcite respectively were used.

Peak height is a measure of the intensity of the reflection if the peak is symmetrical, but is only an approximation if the peak is non symmetrical. However, as the peaks under consideration usually exhibit symmetry about their maximum intensity values, the peak heights may represent accurate intensity values. To compare, for example, the relative abundance of kaolinite to quartz, the 7 Å (kaolinite)/3.34 Å (quartz) peak height ratio was used. The peak heights were measured directly from the recorded chart, above the general background noise.

Discussion of Results

The clay mineral constituting the matrix of the sandstone is dominantly kaolinite. Small quantities of chlorite may contribute slightly to the 7 Å peak of kaolinite, but the effect was considered not to be significant and was ignored.

The ratio of kaolinite to quartz for each sample was plotted against the spontaneous potential observed from the well log at the sample point (Figure 38). No relationship between the relative abundance of clay to quartz and the spontaneous potential was observed. It may be that the semi-quantitative method employed for the determination of the clay abundance was not sensitive enough to explain the observed differences in the spontaneous potential. It is therefore suggested that

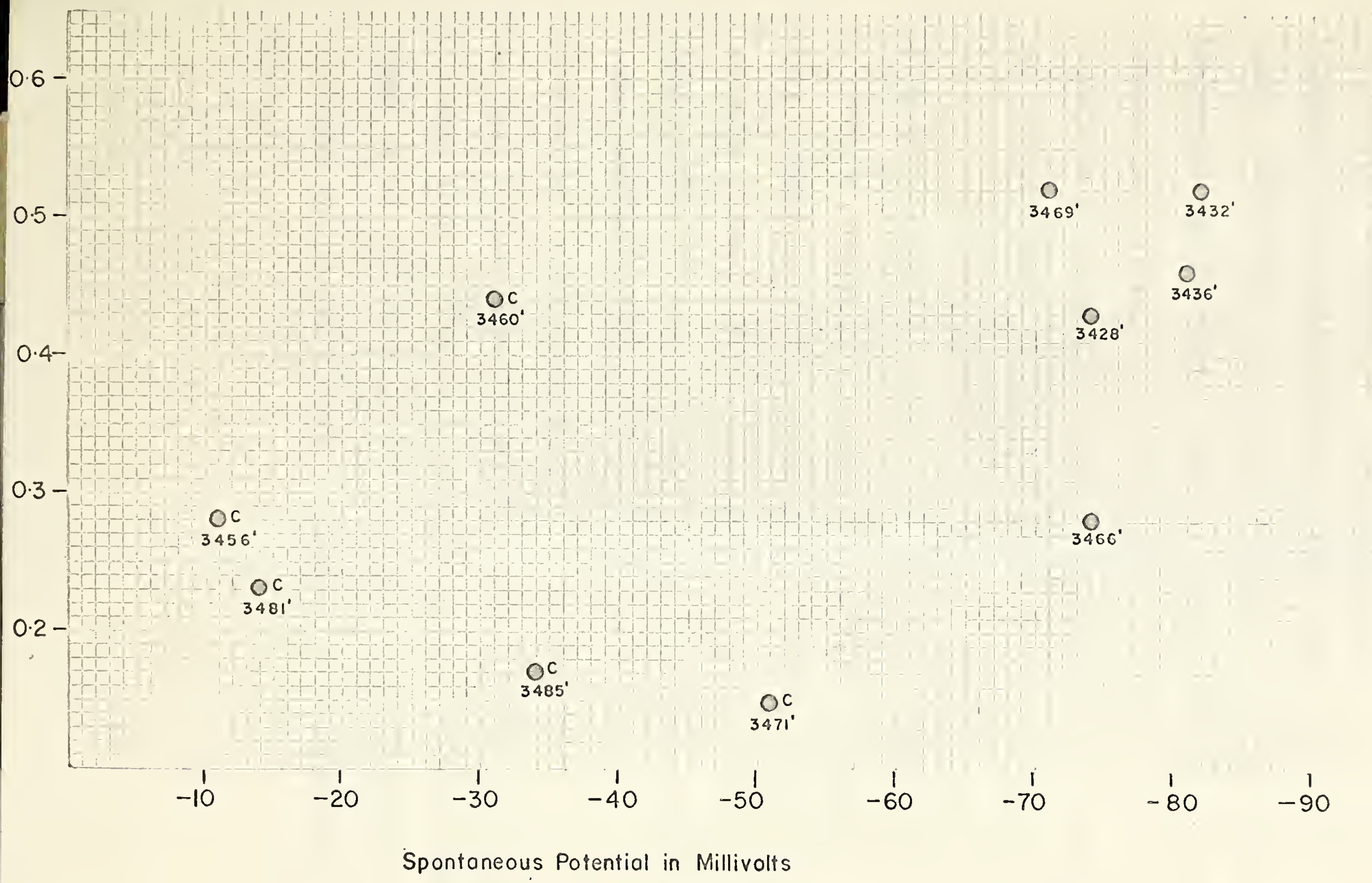


FIGURE 38 Graph showing relationship between spontaneous potential and I_{kaolin}/I_{quartz}.
Note the samples with calcareous cement fall in the left half of the graph

Legend

C Sample with calcareous cement

either a different X-ray technique, using an internal standard, be employed or chemical analysis be done to determine the exact quantity of clay present. A simple chemical method for clay determination was described by Winsauer et al. (1952).

An attempt was made to determine if any non-clay minerals exclusively or in combination with clay minerals affected the spontaneous potential response to a noticeable extent. To do this, the peak heights of each mineral present in the sample were added and the percentage contribution of each peak height or mineral (designated as %Imineral) was calculated. Various combinations of clay and non-clay minerals were tried but no success was achieved in explaining the variations of the observed spontaneous potential. The Table IV shows the various methods employed and the nature of the results obtained.

It is interesting to note in Figure 38 that all the points which fall in the left half of the graph (i.e. having low values of spontaneous potential) are calcareous-cemented sandstones. The 3.01 Å peaks (calcite) were observed in X-ray diffraction patterns and the hand specimens yielded effervescence with dilute hydrochloric acid. This suggests that calcareous cement has reduced the permeability of the sandstones and lowered the spontaneous potential response. It might be advantageous to make further study on the comparison of the spontaneous potential response and the carbonate content of the sandstone. This type of study, made by Griffiths (1958), showed that a large amount of carbonate cement in the sandstone lowered the spontaneous potential. Such carbonate layers act as shale beds with respect to the spontaneous potential curve.

TABLE IV

Spontaneous Potential VS.	(1)	$\frac{I_{kaolin}}{I_{quartz}}$	Scattering of data (Figure 38); the points corresponding to sandstones with calcareous cement fall in the left half of the graph.
	(2)	$\frac{\%I_{quartz}}{\%I_{kaolin} + \%I_{feldspar} + \%I_{calcite}}$	Scattering of data; the points corresponding to sandstones with calcareous cement fall in the left half of the graph.
	(3)	$\frac{\%I_{quartz}}{\%I_{kaolin} + \%I_{feldspar} + \%I_{calcite}} \times \%Matrix$	
	(4)	%Matrix	
	(5)	$I_{calcite}$	Scattering of data.

TABLE V

Well location	Depth	Spontaneous Potential in milivolts	%matrix	Peak Heights Quartz (3.34 Å)	Kaolin (3.56 Å)	Feldspar (3.17 Å)	Calcite (3.01 Å)	$\frac{I_{kaolin}}{I_{quartz}}$
8-4-49-6W5	3428	-74	12.2	186	81	188	-	0.43
"	3432	-82	12.7	152	80	220	-	0.52
"	3436	-81	10.2	168	78	136	-	0.46
"	3439	-70	12.5	126	121	296	-	0.96
"	3456	-11	23.6	110	31	140	96	0.28
"	3460	-31	16.2	90	40	61	124	0.44
"	3466	-74	15.2	124	35	122	-	0.28
"	3469	-71	14.0	118	62	128	-	0.52
"	3471	-51	16.0	76	12	80	220	0.15
"	3481	-14	13.8	84	20	40	196	0.23
"	3485	-34	23.7	142	25	76	92	0.17

CHAPTER FIVE - FORMATION WATER ANALYSIS

RESISTIVITY OF FORMATION WATER IN BASAL BELLY RIVER SANDSTONE

The total amount of mineral content commonly found dissolved in formation waters ranges from a few hundred parts per million (ppm) in practically fresh water up to 300,000 ppm in a heavy brine. The maximum salinity of formation water recorded from the basal Belly River sandstone in the area under study is 29,306 ppm from the Cities Service Keystone 14-22 well (Appendix G, pp. XLIX). The recovery was made while the well was being production tested and is therefore considered to be uncontaminated with drilling fluids. The resistivity as determined by different methods is shown in Table VI.

TABLE VI

Rw determination for Cities Service Keystone 14-22 well

Method*	Analyst	Rw in ohm-m @ 64°F
Direct	Core-Labs. Ltd., Calgary	0.29
Direct	Oil & Gas Cons. Board, Edmonton	0.30
Atlantic	Author (chemical analysis from Oil & Gas Cons. Board, Edmonton)	0.25
Palmer	"	0.31
Spontaneous Potential	Author (using eq.6, p. 100)	0.31
?	Schlumberger (refer Formation Water Resistivity Catalogue)	0.26

* see Appendix H

The value 0.30 @ 64°F obtained by Oil & Gas Conservation Board, Edmonton, using direct method, was used in quantitative interpretation of the spontaneous potential logs.

Water recoveries were made by drill stem testing in four other wells in the area under investigation (Appendix G). Analyses show very low salinities and it is thought that these waters were mainly mud filtrate, and thus were not used.

Representative water resistivity data from the basal Belly River sandstone in the western Canadian sedimentary basin are given in map catalogue "Formation water resistivities covering western Canada" published by Schlumberger (1962) and are reproduced here in Appendix G, pp.xlv). It may be noted that the water resistivity of 0.26 @ 64°F recorded from the Cities Service Keystone 14-22 well is the lowest in the basin, except for Gergen 11-18 well (Lsd.11, Sec.18 Twp.32 Rge.4 W5M.) which has a value of 0.14 ohm m @ 64°F. The possibility of contamination of these waters is very slight.

CHAPTER SIX - SUMMARY AND CONCLUSIONS

This study of the basal Belly River sandstone in the Keystone area, Pembina field, Alberta was undertaken in an attempt to understand the geometry, distribution pattern and petrology of the sandstones and to suggest a possible mode or modes of origin. Attempts were made to relate variations in petrography to variations in the response of the spontaneous potential log. Finally, the geometry, distribution pattern and petrology of the basal Belly River sandstone was related to the accumulation of hydrocarbons.

The study was based on the examination of well logs from about 200 wells which penetrated the basal Belly River sandstone, cores from seven wells and on the behavior of fluids in the wells which were tested.

Structure on the top of the Lea Park Shale consists mainly of a homoclinal dip of about 25 to 30 feet per mile due southwest.

Isopach and Isolith maps of the basal Belly River sandstone show that the sandstone pinches and swells in all directions with a general southeasterly thinning. Though the sandstone is seldom entirely absent, at least 9 local areas of thickening of the sandstone can be delineated.

Anomalies on the structure contour map on the top of the basal Belly River sandstone show that structurally higher areas are underlain by thicker sandstones implying that the upper surfaces of the sandstone bodies are convex upward.

The sandstone-shale ratio map agrees closely with the isopach and isolith maps, and the isopachs and facies contours have similar trends. Maps of spontaneous potential reduction factor and shaliness show that the sandstone bodies are cleaner in their central portion where they are

relatively thick, become progressively more shaly towards the peripheries and eventually pass into shale.

A map showing the number of shale beds within the basal Belly River sandstone has north to northeast trends similar to the trend of the long axes of the sandstone bodies. This may suggest that the fluctuating strand line along which shale beds interfingered with sandstone also had this trend.

Various graphical, analytical and statistical methods were employed to derive residual anomaly maps from the present structural configuration of the top of the Lea Park Formation. It was hoped that these anomalies would approximate pre-Belly River paleotopography of the sea floor, which may have affected the locus of sand accumulation. On the basis of map comparison it does not appear likely that paleotopography on top of the Lea Park had any influence on sand deposition.

Stratigraphic cross sections drawn with datum planes in the underlying Lea Park Shale reveal that the sandstone bodies have flat bottoms and upwardly convex tops. Sandstone bodies seem to have steep western slopes with abrupt facies change whereas their gentle eastern slopes pass gradually into shale. The lobe of basal Belly River sandstone extending southeasterly across the area studied is considered to be an off-lap sequence composed of individual sandstone bodies overlapping so that the body towards the east is stratigraphically higher than the preceding one.

Grain size analyses carried out on eight samples from the basal Belly River sandstone compare well to the deposits of the "near-shore gulf environment" as defined by Shepard and Moore (1955). The sorting coefficients obtained could best be compared with the continental shelf sands below wave base in the genetic sorting

classification adopted by Friedman (1962). In general, the basal Belly River sandstone is not as well sorted, is more argillaceous, and has sand grains more angular than those of many modern beaches and barrier islands.

Megascopically, the basal Belly River sandstone is light to medium grey, "salt and pepper", fine to coarse grained, angular to subrounded, moderately to poorly sorted, calcareous to noncalcareous sandstone which tends to split occasionally along certain bedding planes formed by concentrations of micaceous and carbonaceous material concentrated into thin layers. Specimens show both parallel and low angle cross laminations and are occasionally mottled.

Petrographically, the basal Belly River sandstone is a lithic sandstone in the classification scheme adopted. Chert particles, rock fragments, quartz and feldspars are the essential components. Varietal minerals present are carbonate, biotite and chlorite. Calcite is the usual cement and commonly occurs partially replacing quartz, chert and feldspars.

The dominant heavy minerals present are biotite, garnet, chlorite, zircon, apatite and tourmaline. Heavy minerals present in minor quantities are rutile, andalusite and possibly jarosite.

The principal clay matrix in the basal Belly River sandstone is kaolinite with perhaps a little chlorite. Because kaolinite is a non-swelling type clay with low base exchange capacity and low deflocculating tendency, it should not cause much clogging of the reservoir sands when in contact with extraneous fluids.

The behavior of the spontaneous potential is normal in wells which penetrated the sandstones studied. In places, calcite cement in

the sandstones seems to have reduced spontaneous potential response perhaps by reducing permeability.

The accumulation of hydrocarbons in the sandstone bodies is stratigraphic in nature, independent of structure, and is related to facies change from sandstone to shale. The search for petroleum accumulation in these sandstone bodies is difficult.

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APPENDIX A

LOCATION OF SAMPLES

LOCATION OF SAMPLES

I Particle Size Analysis

Whitehall Keystone 6-3

Lsd. 6, Sec. 3, Twp. 48, Rge. 3 W5M.

Elev. 2833' K.B.

Depth below K.B. (feet)

3197.0
3202.5
3207.0
3214.5

Whitehall Keystone 14-9

Lsd. 14, Sec. 9, Twp. 48, Rge. 3 W5M.

Elev. 2732' K.B.

Depth below K.B. (feet)

3061.5
3074.0
3082.0

Imperial Canadian Superior Berrymoor 8-4C

Lsd. 8, Sec. 4, Twp. 49, Rge. 6 W5M.

Elev. 2737' K.B.

Depth below K.B. (feet)

2425

II Thin Sections

Whitehall Keystone Pembina 8-31

Lsd. 8, Sec. 31, Twp. 47, Rge. 2 W5M.

Elev. 3013' K.B.

* Marks thin sections not used because of very high shale content.

<u>Depth below K.B. (feet)</u>

3314.5
3320.0
*3334.0
3343.0
3347.0
3360.0
3363.0
*3374.0

Whitehall Keystone 14-9

Lsd. 14, Sec. 9, Twp. 48, Rge. 3 W5M.

Elev. 2732' K.B.

Thin sections were supplied by the Whitehall Canadian Oils Ltd., Calgary.

<u>Depth below K.B. (feet)</u>

3063.0
3065.5
3078.0
3090.0
3093.0

III Heavy Mineral Sample

Whitehall Keystone 14-9

Lsd. 14, Sec. 9, Twp. 48, Rge. 3 W5M.

Elev. 2732' K.B.

<u>Depth below K.B. (feet)</u>

3082.0

IV X-ray Diffraction Samples

Oriented Slides

Whitehall Keystone 6-3

Lsd. 6, Sec. 3, Twp. 48, Rge. 3 W5M.

Elev. 2833' K.B.

Depth below K.B. (feet)

3197.0

Whitehall Keystone 14-9

Lsd. 14, Sec. 9, Twp. 48, Rge. 3 W5M.

Elev. 2732' K.B.

Depth below K.B. (feet)

3061.0
3074.0
3082.0

Imperial Canadian Superior Berrymoor 8-4C

Lsd. 8, Sec. 4, Twp. 49, Rge. 6 W5M.

Elev. 2737' K.B.

Depth below K.B. (feet)

2425.0

Non-oriented Slides

Imperial Canadian Superior Berrymoor 8-4C

Lsd. 8, Sec. 4, Twp. 49, Rge. 6 W5M.

Elev. 2737' K.B.

Depth below K.B. (feet)

3428.0	3469.0
3432.0	3471.0
3436.0	3481.0
3439.0	3485.0
3456.0	
3460.0	
3466.0	

APPENDIX B

KEY TO DESCRIPTION OF SANDSTONE CORE SAMPLES

KEY TO DESCRIPTION OF SANDSTONE CORE SAMPLES

(Modified after scheme used by
Core Laboratories - Canada Limited,
Calgary, Alberta.)

Colour

(1) Grey
(2) Brown
(3) "Salt and Pepper"

Induration

(4) Unconsolidated
(5) Soft (easily crushed)
(6) Medium
(7) Hard
(8) Dense (no visible porosity)

Grain Size

(9)	Very fine	(0.0625 mm to 0.125 mm)
(10)	Fine	(0.125 mm to 0.25 mm)
(11)	Medium	(0.25 mm to 0.50 mm diameter)
(12)	Coarse	(0.50 to 1.00 mm diameter)
(13)	Very coarse	(1.0 to 2.0 mm diameter)
(14)	Gravel	(greater than 2.0 mm diameter)

Shale Content

(15)	Shale	(less than 5% sand)
(16)	Sand Lenses	(5% to 45% sand)
(17)	Interbedded	(approx. 50% sand)
(18)	Shale Lenses	(55% to 95% sand)
(19)	Shaly Partings	(over 95% sand)
(20)	Massive sand	(no visible shale)

Broken

(21) Broken or fractured so that one or more tests cannot be made.

Accessory Minerals

(A) Glauconite
(B) Pyrite
(C) Pyrobitumen
(D) Silt or Clay
(E) Oil Stains

APPENDIX C

CORE DESCRIPTIONS

CORE DESCRIPTIONS

Whitehall Keystone Pembina 8-31

Lsd. 8, Sec. 31 Twp. 47, Rge. 2 W5 Mer.

Elev. 3013' K.B.

Core 1 3310-34 Recovery 24'

1'3"	SANDSTONE, medium grained, "salt and pepper", calcareous, white mica flakes, subangular to subrounded.
11"	SANDSTONE, fine grained, "salt and pepper", non calcareous, micromicaceous, subangular to subrounded, occasional carbonaceous partings, cross-stratified, white clay matrix.
3'5"	SANDSTONE, medium grained to fine grained, "salt and pepper, noncalceous, micromicaceous, subangular to subrounded, occasional carbonaceous streaks and partings, cross-stratified, white clay matrix, stray light olive grey noncalcareous claystone pellets, bottom 1" characterized by pebbles (up to 3 cms.) and lenticles of light olive grey noncalcareous claystone, arranged parallel to the contact with underlying shale; contact sharp, irregular and cuts the laminae of the underlying shale suggesting a "scour and fill".
2'4"	SHALE, medium grey to medium dark grey, noncalcareous, silty, carbonaceous, abundant carbonized plant impressions, coal streaks at the top.
5"	COAL, black, brilliant luster, brittle, interlaminated with shale.
8"	SHALE, as above.
1'	SANDSTONE, fine grained, medium grey, silty, slightly calcareous, wavy bedding.
1'3"	SANDSTONE, fine grained, "salt and pepper", noncalcareour massive.
10"	SILTSTONE, medium grey to medium light grey, noncalcareour, patchy appearance of siltstone and shale, grading to shale at bottom.
10"	SHALE, dark grey, noncalcareous, carbonaceous with coal streaks.
7"	CLAYSTONE, light grey, noncalcareous, carbonized plant impressions preserved at all angles.

4'	SHALE and CLAYSTONE interbedded; SHALE medium dark grey, noncalcareous, silty at places, carbonized plant impressions and coal streaks, stray light olive grey claystone pellets.
3'2"	SHALE and CLAYSTONE, as above, bottom part silty with wavy bedding.

Core 2 3334-74 Recovery 40'

2'4"	SILTSTONE and SHALE interlaminated; SILTSTONE light grey, slightly calcareous to noncalcareous, micromicaceous, cross-laminated, SHALE, medium grey, noncalcareous, carbonaceous and micaceous partings, light yellow brown, noncalcareous, claystone bands at bottom, rare convolute bedding.
1'3"	SANDSTONE, fine grained, light grey, "salt and pepper", noncalcareous, silty, micromicaceous, carbonaceous and micaceous partings, irregular laminae of shale present.
2'11"	SANDSTONE, fine grained, light grey, "salt and pepper", calcareous, micromicaceous, subangular to subrounded, carbonaceous and micaceous partings, irregular laminae of shale at bottom, top 3" slightly calcareous.
6"	SHALE, medium dark grey, noncalcareous, silty, carbonaceous, micromicaceous, laminated, bands of light yellow brown claystone.
2'7"	SANDSTONE, fine grained, medium grey, "salt and pepper", calcareous, micromicaceous, subangular to subrounded, shaly and carbonaceous partings, stray occurence of shale lenticles and claystone pebbles, top 8" slightly calcareous and silty.
10'5"	SILTSTONE with interbedded SHALE and SANDSTONE; SILTSTONE, light grey, noncalcareous to slightly calcareous, sandy, micromicaceous, fine coaly streaks, carbonaceous at partings, well bedded, occasionally cross-laminated, at times wavy, SANDSTONE, fine grained, light grey, slightly calcareous, silty, micromicaceous, carbonaceous and micaceous partings, 1" pale yellow brown claystone at bottom, bottom contact with sandstone irregular.
2'8"	SANDSTONE, fine grained, light grey, "salt and pepper", calcareous to slightly calcareous, micromicaceous, subangular to subrounded, carbonaceous and micaceous partings, claystone pebbles (up to 25 cms. in diam.) observed at 13 cms. from bottom, pebbles are moderate yellow brown, slightly calcareous and flattened along the bedding planes, irregular dark grey shale fragments floating in the sand at bottom.

1'9"	SILTSTONE, light grey, noncalcareous, micromicaceous, scattered carbonaceous matter, random bands of moderate yellowish brown claystone, irregular patches and laminae of medium grey shale.
2'2"	SANDSTONE, fine grained, medium light grey, "salt and pepper", silty, calcareous to slightly calcareous, micromicaceous, subangular to subrounded, carbonaceous and micaceous at bedding planes, 1" shale bed at 10" from the bottom, Shale, medium dark grey, noncalcareous, carbonaceous and micaceous.
2'	SHALE, medium dark grey, noncalcareous at places, silty, micromicaceous, slightly carbonaceous, slabby.
2'8"	SANDSTONE, fine grained, light grey, "salt and pepper", calcareous, micromicaceous, subangular to subrounded, carbonaceous and micaceous at partings, bottom 5" silty and noncalcareous.
8'9"	SHALE, medium dark grey to dark grey, noncalcareous, silty with silty bands and lenses, micromicaceous, scattered carbonaceous matter, irregularly laminated.

Whitehall Keystone 6-3

Lsd. 6, Sec. 3, Twp. 48, Rge. 3W5 Mer.

Elev. 2833' K.B.

Core 1 3165-3215 Recovery 50'

2'5"	SHALE, medium grey to medium dark grey, noncalcareous, slightly silty, carbonaceous with coal streaks, carbonized plant impressions, top 3" is claystone with underlying 2" of coaly shale, bottom grading to coaly shale.
7"	COAL
1'4"	SHALE, medium grey, noncalcareous, irregular laminae, streaks and patches of siltstone, top 4" is carbonaceous shale.
2'4"	SHALE, medium grey to medium dark grey, noncalcareous, slightly silty, abundant carbonized plant impressions, fissile.

3'1"	SILTSTONE and SHALE; SILTSTONE, light grey, slightly calcareous to noncalcareous, occurs as irregular cross-laminae in shale, carbonaceous partings, occasional occurence of light olive grey, noncalcareous claystone, claystone occur as "pinch and swell" or as irregular laminae ¼"-½" in thickness; shale, as above.
1'11"	SILTSTONE and SHALE, as above, bottom 1½" is coarse siltstone, slightly calcareous with coal streaks, contact with underlying coal bed irregular.
2"	COAL
5"	SILTSTONE and SHALE, as above.
1'2"	SHALE, dark grey, noncalcareous, carbonaceous with fine coal streaks, abundant carbonized plant impressions, fissile.
1'3"	SILTSTONE, light grey, noncalcareous, sandy with sand patches, occasional irregular scattered laminae of shale, occasional carbonaceous partings, dense.
1'8"	SILTSTONE, light grey, noncalcareous, laminated with shale, carbonaceous partings.
1'10"	SHALE, medium dark grey, noncalcareous, occasional silty lenses, bottom 3" is carbonaceous shale.
9"	COAL
1'5"	SHALE, light grey, noncalcareous, grading to siltstone at bottom.
1'4"	SILTSTONE, light grey, noncalcareous, fine sandy patches, occasional irregular laminae of shale, scattered carbonaceous matter, few carbonized streaks across the bedding plane, carbonized plant impressions, carbonaceous and micaceous at partings.
1'8"	SANDSTONE, fine to medium grained, "salt and pepper", slightly calcareous, stray patches and laminae of shale, few carbonaceous and micaceous partings, dense.
9"	SANDSTONE, medium to fine grained, calcareous, rest as above.
5'2"	SANDSTONE, medium to fine grained, "salt and pepper", noncalcareous to slightly calcareous, micromicaceous, few carbonaceous and micaceous partings, clay matrix, load cast at bottom.
2"	SHALE, medium grey, noncalcareous, silty, carbonaceous and micaceous.

3'8"	SANDSTONE, medium grained, "salt and pepper", calcareous, micromicaceous, clay matrix, dense, top 1" slightly calcareous.
1'10"	SANDSTONE, fine grained, "salt and pepper", calcareous, clay matrix, dense.
2'10"	SANDSTONE, medium grained, "salt and pepper", noncalcareous floating laminae of shale, occasional coal streaks, claystone pebble (6 cms. x 3 cms.) at 2" from top flattened along the bedding plane, mud pebbles (medium grey) and claystone pebbles (light olive grey) common between 2" and 10" from top.
1'1"	SANDSTONE, slightly calcareous, rest as above, claystone pebble (4 cms. x 1.5 cms.) at 4" from top.
3'4"	SANDSTONE, noncalcareous, rest as above, claystone patches along the bedding plane at 1' 1" from top, scattered chunks of claystone (up to 4½ cms. x 2 cms.), bottom 4" fine grained, slightly calcareous sandstone.
7"	SANDSTONE, slightly calcareous, rest as above.
7"	SANDSTONE, calcareous, rest as above.
1'9"	SANDSTONE, medium to fine grained, noncalcareous, rest as above.
1'9"	SANDSTONE, fine to medium grained, rest as above.

Whitehall Keystone 14-9

Lsd. 14, Sec. 9, Twp. 48, Rge. 3 W5 Mer.

Elev. 2732' K.B.

Core 1 3045-3090 Recovery 45'

2'7"	SHALE and SILTSTONE, interbedded and intermixed, SHALE, medium grey, very silty, noncalcareous, abundant carbonized plant impressions along bedding planes, micromicaceous, SILTSTONE, sandy, slightly calcareous, abundant dark mica with occasional white mica flakes, scattered coaly matter, cross-laminated, clay matrix.

1'8"	SHALE, medium light grey, noncalcareous, slightly silty along bedding planes, micromicaceous, occasional carbonized plant impressions, cross-laminae of siltstone, noticeable pinch and swelling of light olive grey claystone superficially resembling concretions.
4"	SHALE, dark grey, coaly, noncalcareous, micromicaceous.
4"	COAL, black, brilliant luster, brittle and conchoidal, burns with smoky flame, bottom 2" cross-laminated with shale.
4'4"	SHALE, medium grey, noncalcareous, micromicaceous, occasional carbonized plant impressions, wavy bedding, sporadic bands of olive grey mudstone and few cross-laminated greenish grey siltstone bands.
8"	SILTSTONE, greenish grey, noncalcareous, micromicaceous, wavy bedding, intermixed and intertongued with dark grey shale, "involute" folding with truncated crests suggest a penecontemporaneous flow of material and partial erosion prior to deposition of the next overlying stratum.
2'3"	SANDSTONE, fine to medium grained, "salt and pepper", calcareous, scattered coal fragments, micromicaceous, subangular to subrounded, cemental with white clay matrix, massive, load casts at bottom formed by bulbous pockets of sandstone which project downward with sharp contact into the underlying shale, suggesting probably a "scour and fill".
11"	SHALE, medium light grey, noncalcareous, silty, micromicaceous, cross-laminae of siltstone, wavy and "convolute" folding, curved pointed tongues of underlying sandstone penetrating into shale are here described as "flame structures". Associated with "flame structures" are irregular "fragments" of shale included in the more mobile sands. In the bottom portion are also "inclusions" of pale yellowish brown claystone. It is to be noted that the "flame structures" described here are opposite to those described by Walton (1956) as tongues of shale in the overlying sandstone.
1'10"	SANDSTONE, medium grained, "salt and pepper", calcareous, subangular to subrounded, occasional carbonized wood stem remains, sporadic occurence of claystone chunks and lenticles (size up to 60 mm.), medium light grey, noncalcareous, micromicaceous.
1'6"	SANDSTONE, medium grained, "salt and pepper", noncalcareous, subangular to subrounded, friable, porous and permeable, sporadic occurence of claystone chunks and lenticles as described above, load casts at bottom.

4"	SHALE, medium grey, silty, noncalcareous, micromicaceous.
1'7"	SANDSTONE, medium grained, "salt and pepper", noncalcareous, subangular to subrounded, friable, porous and permeable, sporadic occurence of claystone pebbles (4-40 mm. in diameter) studded with sand grains on the outside, pebbles slightly flattened along the bedding planes, occasional shale lenticles, top contact with shale gradational (decreasing grain size), bottom contact with shale irregular.
8"	SHALE, medium dark grey, noncalcareous, micromicaceous, cross-laminae of siltstone.
1'5"	SANDSTONE, medium grained, "salt and pepper", slightly calcareous, micromicaceous, subangular to subrounded, white clay matrix, cross-stratified, contains occasional lenticles of coal.
7"	SANDSTONE, fine grained, rest as above.
1'9"	SANDSTONE, medium grained, slightly calcareous, rest as above.
1'10"	SHALE, medium light grey, noncalcareous, micromicaceous, scattered carbonaceous matter, cross-laminae of siltstone.
4'	SANDSTONE, medium grained "salt and pepper" noncalcareous, subangular to subrounded, porous and permeable, occasional carbonaceous streaks, sporadic occurence of claystone chunks, light medium grey, noncalcareous and micromicaceous, few light olive grey pellets of claystone, carbonaceous shaly partings with white mica flakes.
5"	SHALE, dark grey to medium grey, noncalcareous, carbonaceous with coal streaks, cross-laminae of siltstone.
2'	SANDSTONE, medium grained, "salt and pepper", calcareous to slightly calcareous, subangular to subrounded, stray pellets of light olive grey claystone.
3'4"	SANDSTONE, medium to fine grained, "salt and pepper", slightly calcareous to noncalcareous, micromicaceous, subangular to subrounded, white clay matrix, carbonaceous shaly partings with white mica flakes.
4'3"	SANDSTONE, calcareous, rest as above.

Cities Service Warburg Keystone Pembina 14-16

Lsd. 14, Sec. 16, Twp. 48, Rge. 3 W5 Mer.

Elev. 2752' K.B.

Core 1 3072-3092 Recovery 20'

10'	Missing
6"	SANDSTONE, fine to medium grained, "salt and pepper", slightly calcareous, dense.
5'5"	SANDSTONE, fine to medium grained, "salt and pepper", calcareous, scattered carbonaceous matter, stray occurence of claystone nodules (up to 3 cms. x 2 cms.), few carbonaceous and micaceous partings, dense.
¼"	SHALE, medium dark grey, noncalcareous.
2'2"	SANDSTONE, medium grained, "salt and pepper", slightly calcareous to noncalcareous, soft, oil stained.
1'	SANDSTONE, medium grained, "salt and pepper", carbonaceous and micaceous partings, soft, oil stained.

Core 2 3093-3118 Recovery 25'

1'8"	SANDSTONE, as above.
2'4"	SANDSTONE, fine to medium grained, rest as above.
5'	Missing.
8"	SANDSTONE, medium grained, rest as above.
2'	SANDSTONE, medium to fine grained, "salt and pepper", calcareous, hard.
1'7"	SANDSTONE, fine to medium grained, "salt and pepper", noncalcareous, soft, oil stained.
1'3"	SANDSTONE, medium grained, rest as above.
1'7"	SANDSTONE, fine to medium grained, "salt and pepper", noncalcareous, medium, oil stained.
1'4"	SANDSTONE, medium grained, "salt and pepper", noncalcareous, occasional carbonized plant impressions and coal streaks, soft, oil stained.
5'	Missing.

Cities Service Warburg Keystone Pembina 16-18

Lsd. 16, Sec. 18, Twp. 48, Rge. 3 W5 Mer.

Elev. 2699' K.B.

Core 1 3063-88 Recovery 24'

1'3"	SANDSTONE, fine grained, "salt and pepper", slightly calcareous to noncalcareous, shaly and micaceous partings, hard.
9"	SANDSTONE, fine to medium grained, "salt and pepper", slightly calcareous, top 2" medium grained calcareous sandstone, rest as above.
1'	SANDSTONE, fine to medium grained, slightly calcareous to noncalcareous, ½" claystone bed at 1" from top, cross-laminae of siltstone in top 5" portion, bottom contact with shale irregular, rest as above.
2"	SHALE, medium dark grey, noncalcareous.
9"	SANDSTONE, medium grained, "salt and pepper", calcareous, slightly carbonaceous, micaceous partings, medium.
8"	SANDSTONE, medium grained, "salt and pepper", calcareous, medium, top 4" fine to medium grained, slightly calcareous.
6"	SANDSTONE, medium grained, "salt and pepper", noncalcareous, siltstone and shale laminae, laminae dipping less than 5^{o}.
7"	SANDSTONE, fine to medium grained, "salt and pepper", noncalcareous, few carbonaceous and micaceous partings.
2"	SILTSTONE, light grey, noncalcareous.
5"	SHALE, medium dark grey, noncalcareous, lenses and patches of siltstone, claystone between 3" and 4" from top.
1'5"	SANDSTONE, medium grained, "salt and pepper", noncalcareous, slightly carbonaceous and micaceous partings, top 3" cross-laminated at low angle with shale, top grading to siltstone.
8"	SANDSTONE, medium grained, "salt and pepper", calcareous, slightly carbonaceous, micaceous partings, medium.
10"	SANDSTONE, medium grained, "salt and pepper", noncalcareous, cross-laminated with shale.
11"	SANDSTONE, medium to fine grained, "salt and pepper", calcareous, cross-laminated with shale, stray occurence of claystone.

2'	SANDSTONE, fine to medium grained, "salt and pepper", noncalcareous, medium, bottom 2" calcareous, sharp contact with underlying shale.
2½"	SHALE, medium dark grey, noncalcareous, carbonaceous matter present.
7"	SANDSTONE, fine grained, "salt and pepper", noncalcareous, irregular laminae of shale, dense, bottom contact with shale displaying "flame structure" and minor load casts.
11"	SANDSTONE, fine to medium grained, "salt and pepper", calcareous, hard, claystone pebbles (3 cms. x 2 cms.) and mud pebbles (4 cms. x 3½ cms.) @ 8" from top.
1'5"	SANDSTONE, medium to fine grained, "salt and pepper", slightly calcareous, shale laminae present, hard, top 4" noncalcareous and bottom 4" calcareous.
1'	SANDSTONE, fine to medium grained, "salt and pepper", noncalcareous, dense.
5"	SANDSTONE, fine to medium grained, "salt and pepper", noncalcareous, shale laminae present, carbonaceous, and micaceous partings, dense.
2½"	SILTSTONE, light grey, noncalcareous.
10"	SHALE, medium dark grey, noncalcareous, silty, occasional streaks of siltstone.
1'7"	SANDSTONE, fine grained, "salt and pepper", noncalcareous, dense.
1'1"	SILTSTONE and SHALE; siltstone, light grey, noncalcareous, up to 1" thick cross-laminated, Shale, dark grey, noncalcareous, slightly silty up to 4" thick.
7"	SHALE, dark grey, noncalcareous with irregular patches and lenses of siltstone.

Imperial Canadian Superior Berrymoor 8-4C

Lsd. 8, Sec. 4, Twp. 49, Rge. 6 W5 Mer.

Elev. 2737' K.B.

Note: Core described in the field by Dr. J. F. Lerbekmo, Department of Geology, University of Alberta.

Core 1 3425-3475

5'	SANDSTONE, medium to coarse grained, medium light grey, cross-laminated between 3427½' and 3428½'.
10'6"	SANDSTONE, as above, faint indications of bedding.
3'6"	MUDSTONE, medium dark grey, plant fragments, strongly contorted mixed with fine sandstone, fine sandstone (sideritic) between 3441.5' and 3442'.
6"	SANDSTONE, fine grained with irregular shale partings.
6"	COAL, with upper abrupt contact with sandstone.
2'6"	MUDSTONE and SHALE, with coal fragments, laminated with fine sandstone between 3446' and 3446.5'.
6"	SANDSTONE, medium grained.
2'6"	MUDSTONE, medium dark grey, sandy, poorly bedded.
2'	MUDSTONE, with irregular interbedded fine sandstone, occasional coal lenses (less than ¼") and sideritic lenses (less than 1" thick).
1'6"	SANDSTONE, fine to medium grained, clean.
1'6"	SANDSTONE, fine to medium grained, with thin irregular shale laminae, slightly sideritic.
3'	SANDSTONE, medium grained, "massive" with thin shale laminae at 3458'.
5'	SANDSTONE, coarse grained, "massive", calcite cement.
10'6"	SANDSTONE, medium to coarse grained.

Core 2 3475-3500

10'6"	SANDSTONE, as above, with occasional carbonaceous partings with greenish color, sharp contact with underlying shale.

1'	MUDSTONE, with carbonaceous remains, grading down into fine green-grey sandstone.
2'6"	SANDSTONE, fine grained, green-grey, with even fine laminations of shale.
3'	SANDSTONE, fine grained, faint laminations, mostly massive.
2'	SANDSTONE, fine grained and SHALE, dark grey interbedded (6").
2'	SANDSTONE, fine grained.
1'	SANDSTONE and SHALE interbedded.
1'	SANDSTONE, fine grained with shale laminations.
1'	SANDSTONE and SHALE, interlaminated and interbedded.

APPENDIX D

THIN SECTIONS DESCRIPTIONS

THIN SECTION DESCRIPTION

Whitehall Keystone Pembina 8-31

Lsd. 8, Sec. 31, Twp. 47, Rge. 2 W5M.

Depth - 3314.5 Feet

Texture: Medium-grained sandstone, subangular to subrounded, poor sorting, porosity less than 5%, an argillaceous matrix binds the grains.

Mineralogy: Siliceous rock fragments, 65% - mainly argillite grains and chert; quartz and quartzite, 20%; feldspar, 5% - some fresh and some altered; Matrix, 10% - composed of kaolin and some micaceous material.

Classification: Lithic sandstone

Depth - 3320 Feet

Texture: Fine-grained sandstone, subangular to angular, medium sorting, porosity about 15%, argillaceous and micaceous matrix bind the grains.

Mineralogy: Siliceous rock fragments, 55% - mainly argillite grains and some chert; quartz and quartzite, 30%; feldspar, 10% - fresh and some altered; Matrix, 5% - composed of kaolin , chlorite and other micaceous material.

Cement: Slight as silica overgrowths.

Classification: Lithic sandstone.

Depth - 3343 Feet

Texture: Fine-grained sandstone, subangular to subrounded, medium sorting, very slight or no porosity, argillaceous and micaceous matrix bind the grains.

Structure: Parallel bedding with slight contortion of coal streaks and mica flakes along the bedding planes.

Mineralogy: Siliceous rock fragments, 50% - mainly argillite grains and chert; quartz and quartzite, 30%; feldspar 15% - mostly fresh and some altered; Matrix, 5% - composed of argillaceous material. Some chlorite (1%) occur as detrital grains.

Cement: Chlorite (1%) as coating around the clastic grains.

Classification: Lithic sandstone.

Depth - 3347 Feet

Texture: Fine-grained sandstone, subangular to angular, medium sorting, porosity less than 5%, calcite cement present.

Mineralogy: Siliceous rock fragments, 50% - mainly argillite grains and some chert; quartz and quartzite, 30%; feldspar 10% - partially altered and some fresh.

Cement: Total cement 10% as calcite binding the detrital grains, also partially replaces feldspar and corrodes the boundary of quartz and chert.

Classification: Lithic sandstone.

Depth - 3360 Feet

Texture: Very fine-grained sandstone, angular to subangular, medium

sorting, porosity less than 10%, mostly chloritic cement binds the grains.

Mineralogy: Siliceous rock fragments, 60% - mostly argillite grains; feldspar, 20% - mostly altered and some fresh; quartz and quartzite, 10%; some chlorite (1%) occur as detrital grains.

Cement: Total cement 10% chlorite as coating on detrital grains or partially replacing feldspar.

Classification: Lithic sandstone.

Depth - 3363 Feet

Texture: Fine-grained sandstone, subangular to subrounded, medium sorting, porosity less than 10%, calcite cement present.

Mineralogy: Siliceous rock fragments, 45% - mostly argillite grains; quartz and quartzite, 30%; feldspar, 15% - mostly altered, some fresh; some chlorite (1%) occur as detrital grains.

Cement: Total cement 10% as calcite, at places partially replacing feldspar and corroding the boundary of quartz grains.

Classification: Lithic sandstone.

Whitehall Keystone 14-9

Lsd. 14, Sec. 9, Twp. 48, Rge. 3 W5M.

Depth - 3063 Feet

Texture: Medium-grained sandstone, subangular to angular, fairly good sorting, very slight or no porosity, calcite cement present.

Mineralogy: Siliceous rock fragments, 50% - argillite grains and chert; quartz and quartzite, 25%; feldspar, 10% - partially altered and some fresh euhedral crystals.

Cement: Total cement 15% as calcite binding the detrital grains, also partially replaces feldspar and corrodes the boundary of quartz and chert.

Classification: Lithic sandstone.

Depth - 3065.5 Feet

Texture: Coarse-grained sandstone, subangular to subrounded, medium sorting, porosity about 20%, cementation slight as silica overgrowths.

Mineralogy: Siliceous rock fragments, 60% - mainly chert and argillite grains; quartz and quartzite, 20%; feldspar 20% - partially altered, some fresh; some detrital chlorite (1%) grains.

Cement: Slight silica overgrowths on quartz.

Classification: Lithic sandstone.

Depth - 3078 Feet

Texture: Medium-grained sandstone, subangular to angular, medium sorting, porosity about 15%, cementation slight as silica overgr owths.

Mineralogy: Siliceous rock fragments, 60% - mainly argillite grains and chert; quartz and quartzite, 20%; feldspar, 20% - partially altered, some fresh.

Cement: Slight silica overgrowths on quartz

Classification: Lithic sandstone.

Depth - 3090 Feet

Texture: Medium-grained sandstone, subangular to subrounded, poor sorting, porosity about 15%, calcite cement present.

Mineralogy: Siliceous rock fragments, 50% - mainly argillite grains and some chert; quartz and quartzite, 25%; feldspar, 20% - partially altered, some fresh.

Cement: Total cement 5% as calcite, at places replacing feldspars and corroding the boundary of quartz grains.

Classification: Lithic sandstone.

Depth - 3093 Feet

Texture: Medium-grained sandstone, subangular to subrounded, poor sorting, porosity about 15%, cementation slight as silica overgrowths.

Mineralogy: Siliceous rock fragments, 60% - mainly argillite grains and some chert; quartz and quartzite, 20%; feldspar, 20% - partially altered; some detrital chlorite grains (1%).

Cement: Slight silica overgrowths on quartz.

Classification: Lithic sandstone.

APPENDIX E

LITHOLOGS OF WELLS WITH ELECTROLOGS

LEGEND FOR LITHOLOGS

Sandstone

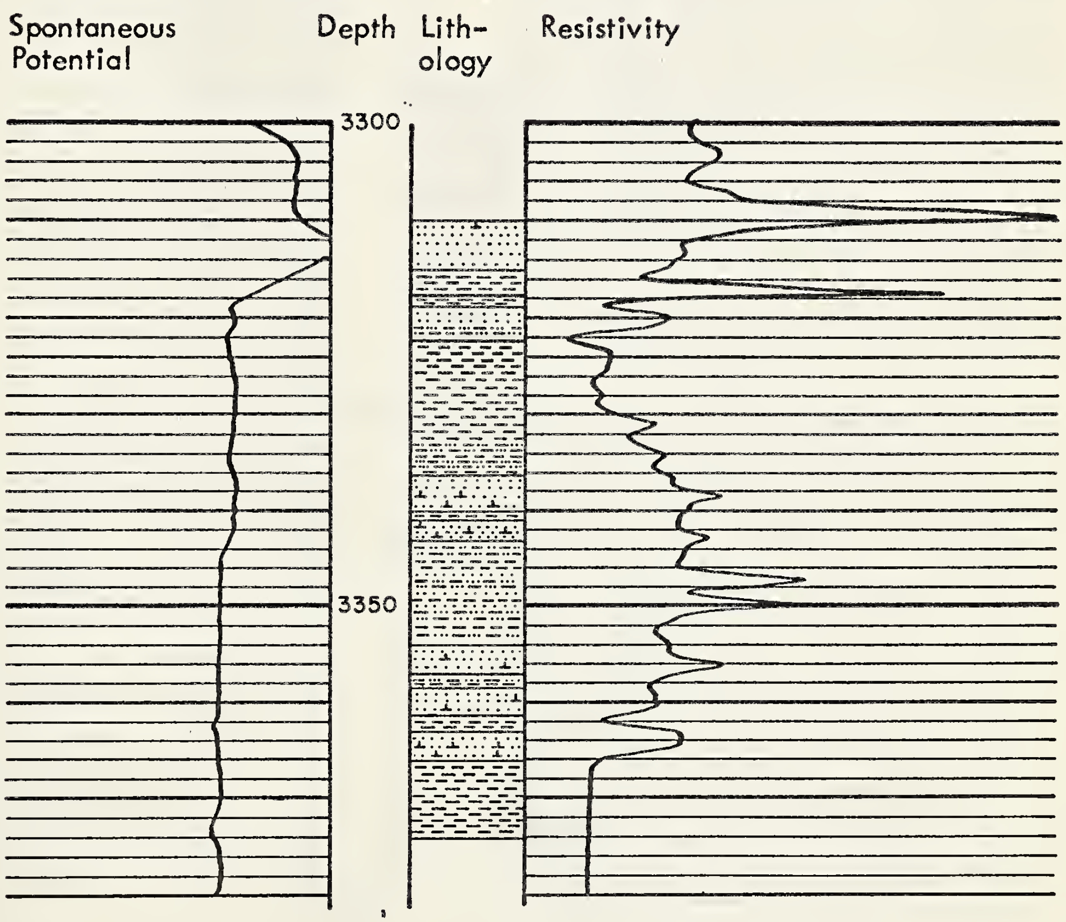
Siltstone

Shale

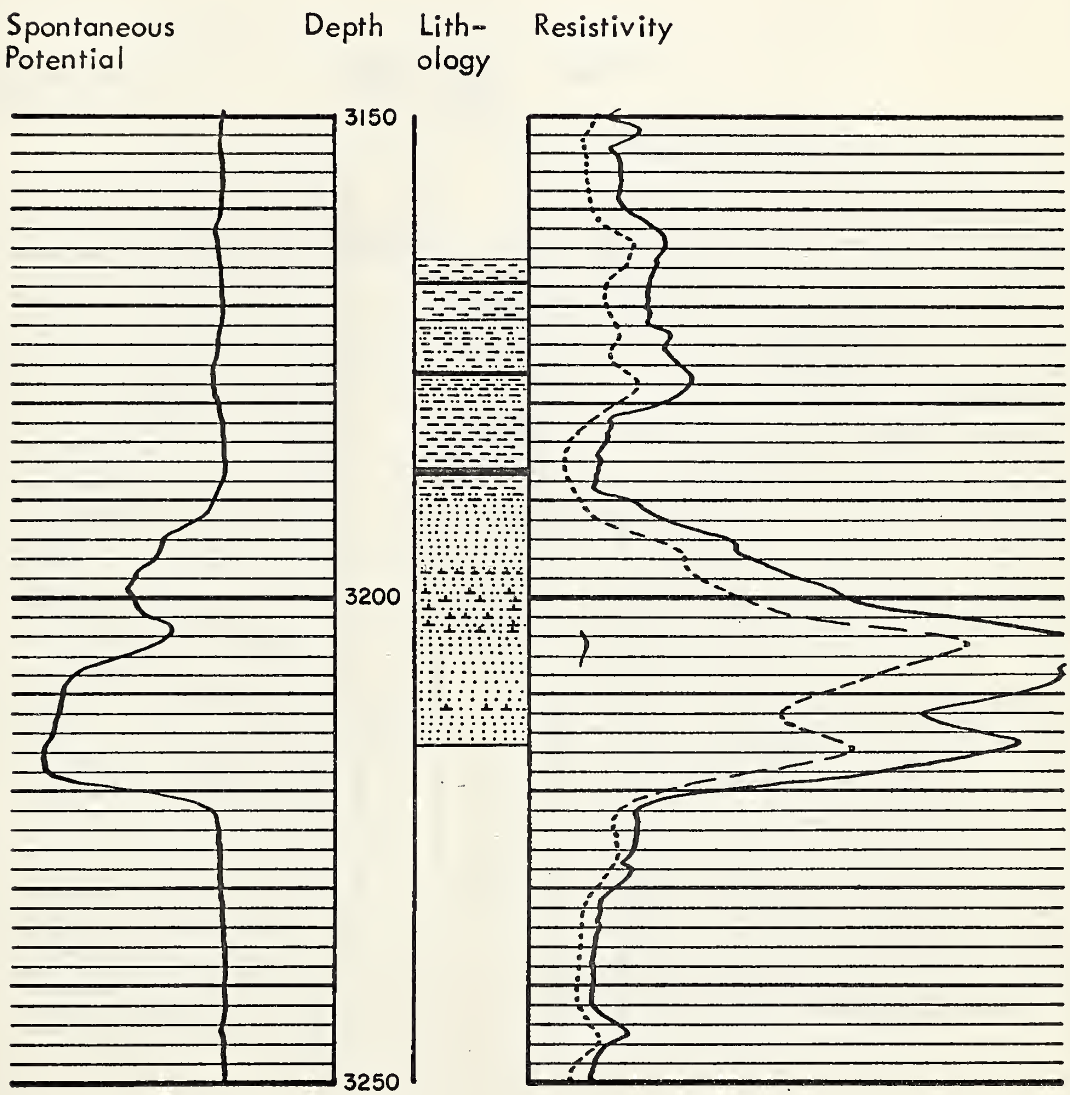
Coal and carbonaceous shale

Calcareous cement

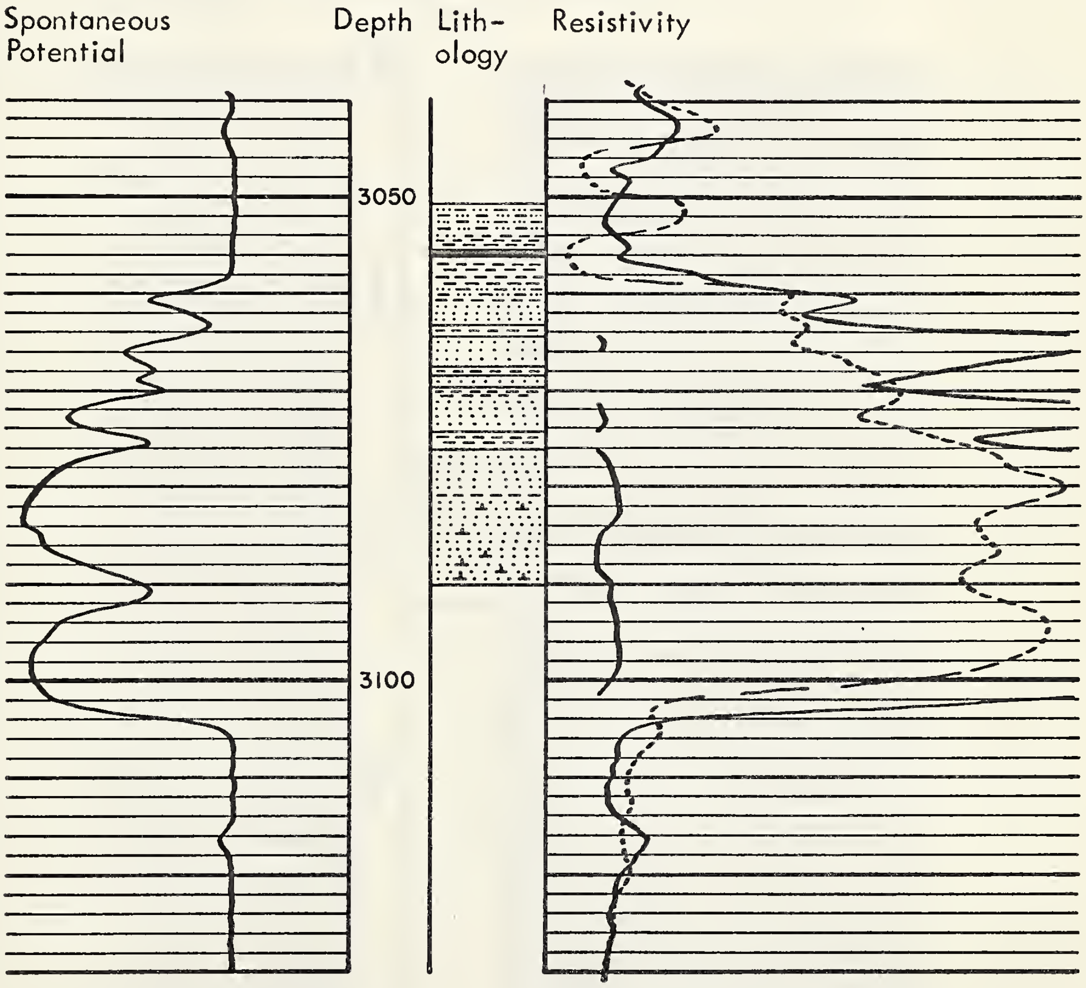
Whitehall Keystone Pembina 8-31
Lsd. 8, Sec. 31, Twp. 47, Rge. 2, W5M
Elev. 3013 ft. (K.B.)



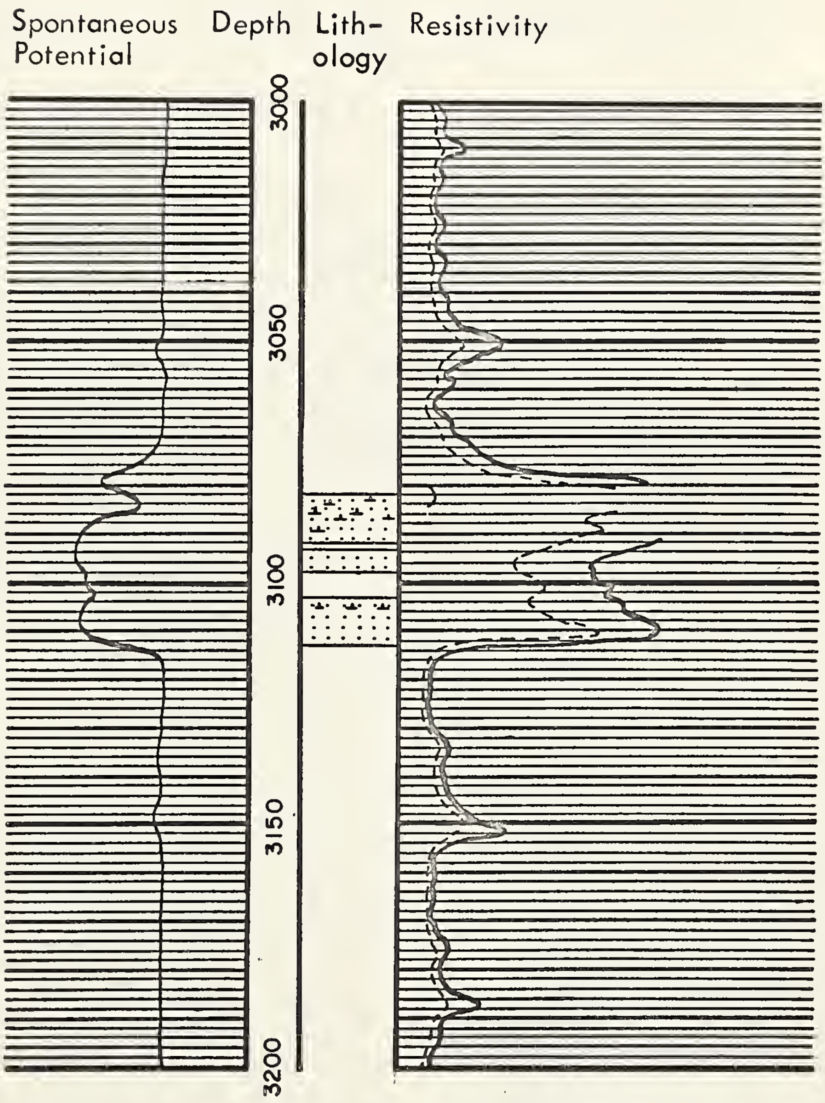
Whitehall Keystone 6-3
Lsd. 6, Sec. 3, Twp. 48, Rge. 3, W5M
Elev. 2833 ft. (K.B.)



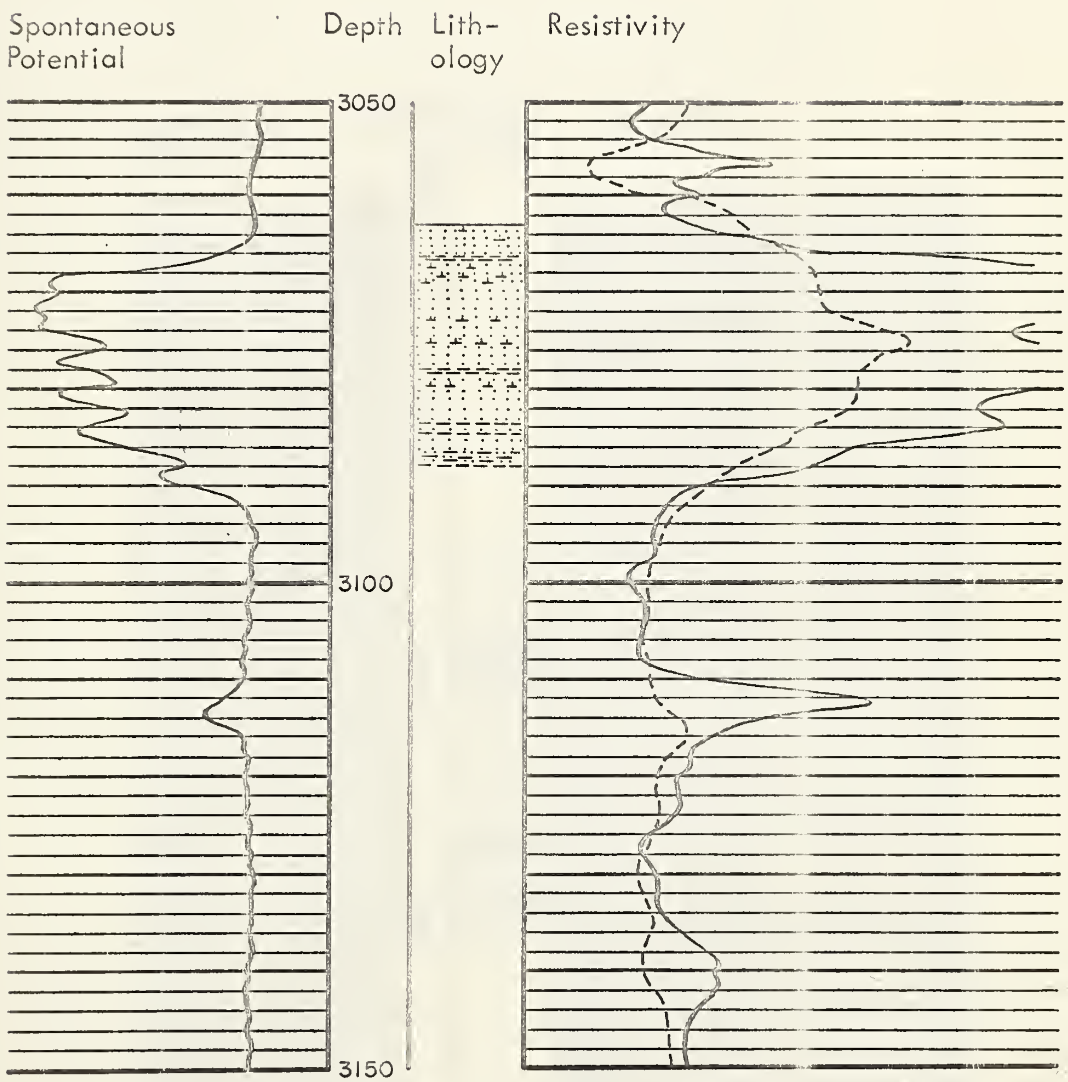
Whitehall Keystone 14-9
Lsd. 14, Sec. 9, Twp. 48, Rge. 3, W5M
Elev. 2732 ft. (K.B.)



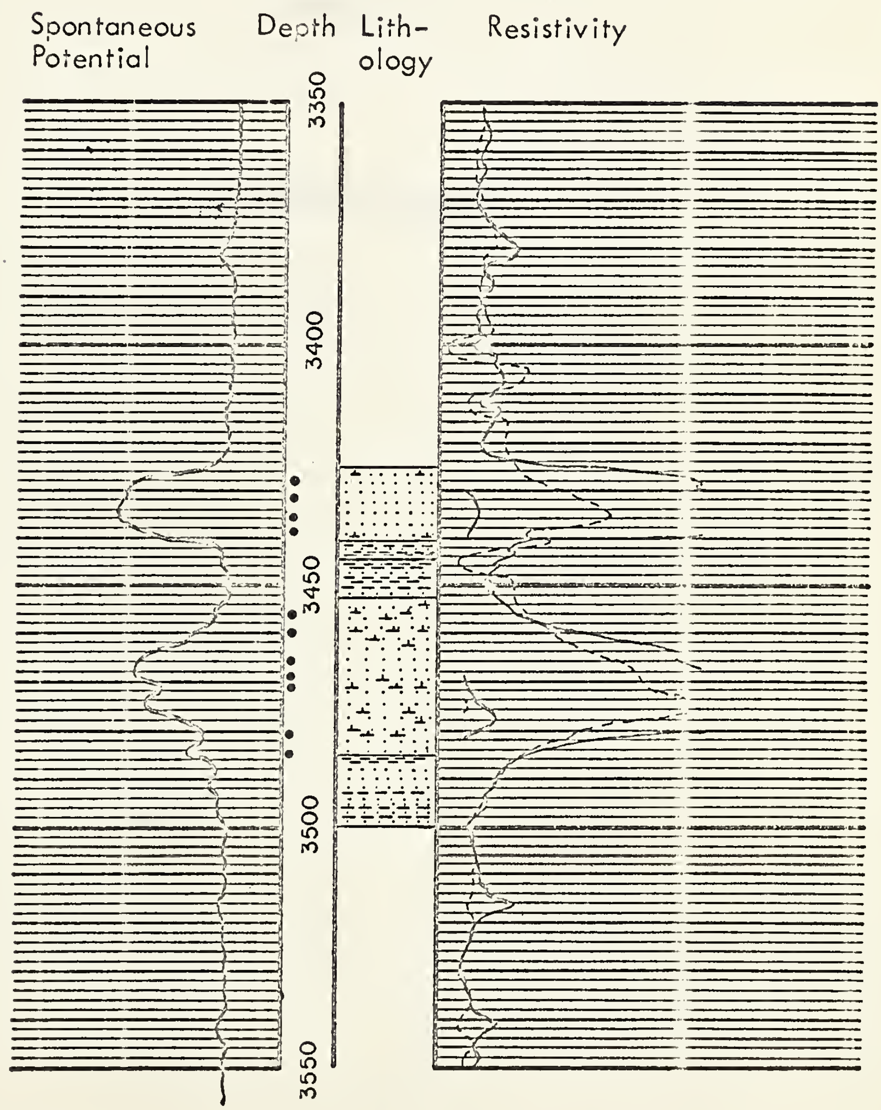
Cities Service Warburg Keystone Pembina 14-16
Lsd. 14, Sec. 16, Twp. 48, Rge. 3, W5M
Elev. 2752 ft. (K.B.)



Cities Service Warburg Keystone Pembina 16-18
Lsd. 16, Sec. 18, Twp. 48, Rge. 3, W5M
Elev. 2699 ft. (K.B.)



Imperial Canadian Superior Berrymoor 8-4C
Lsd. 8, Sec. 4, Twp. 49, Rge. 6 W5M
Elev. 2737 ft. (K.B.)



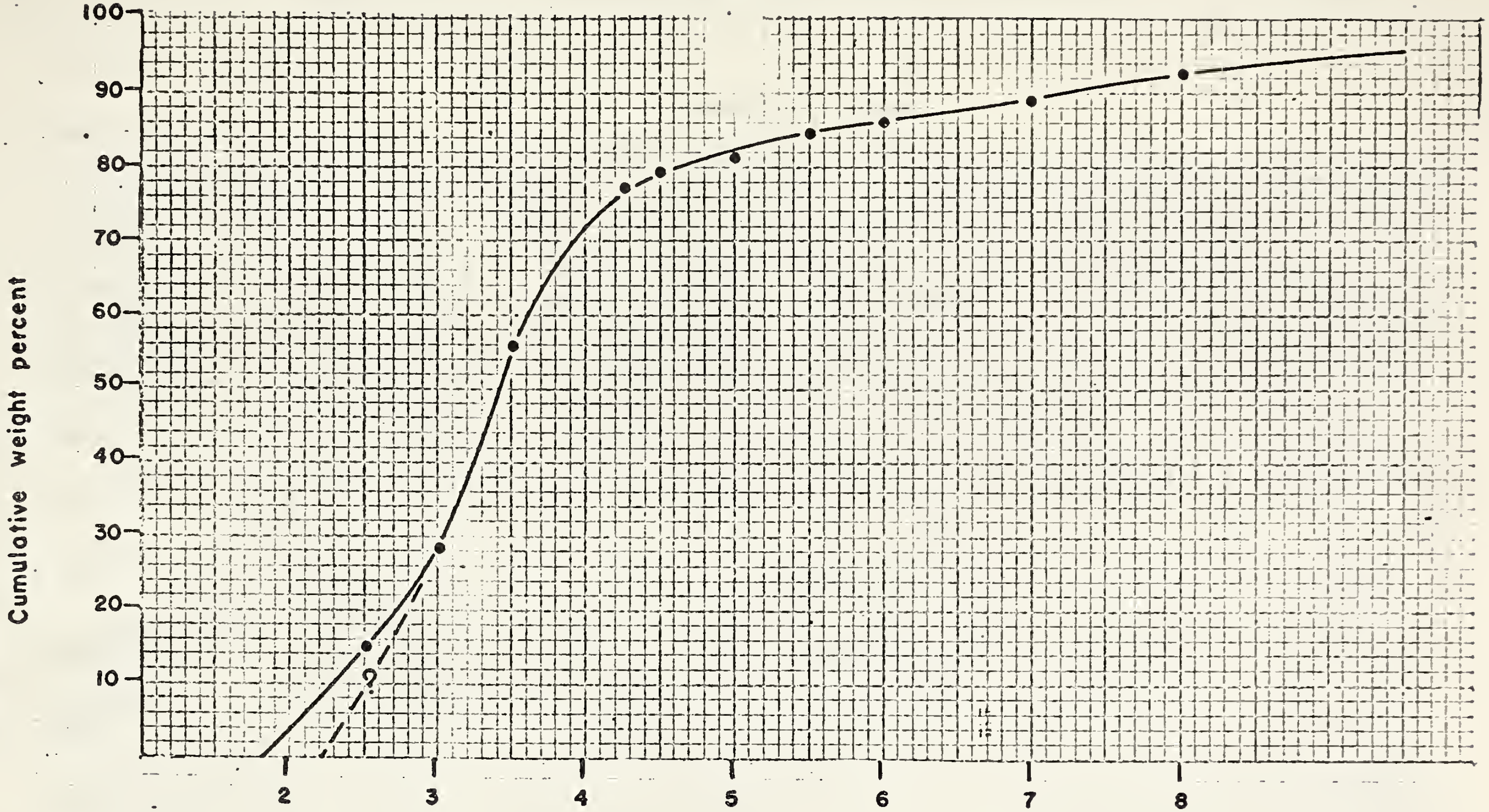
LEGEND

• X-ray diffraction sample

APPENDIX F

CUMULATIVE CURVES

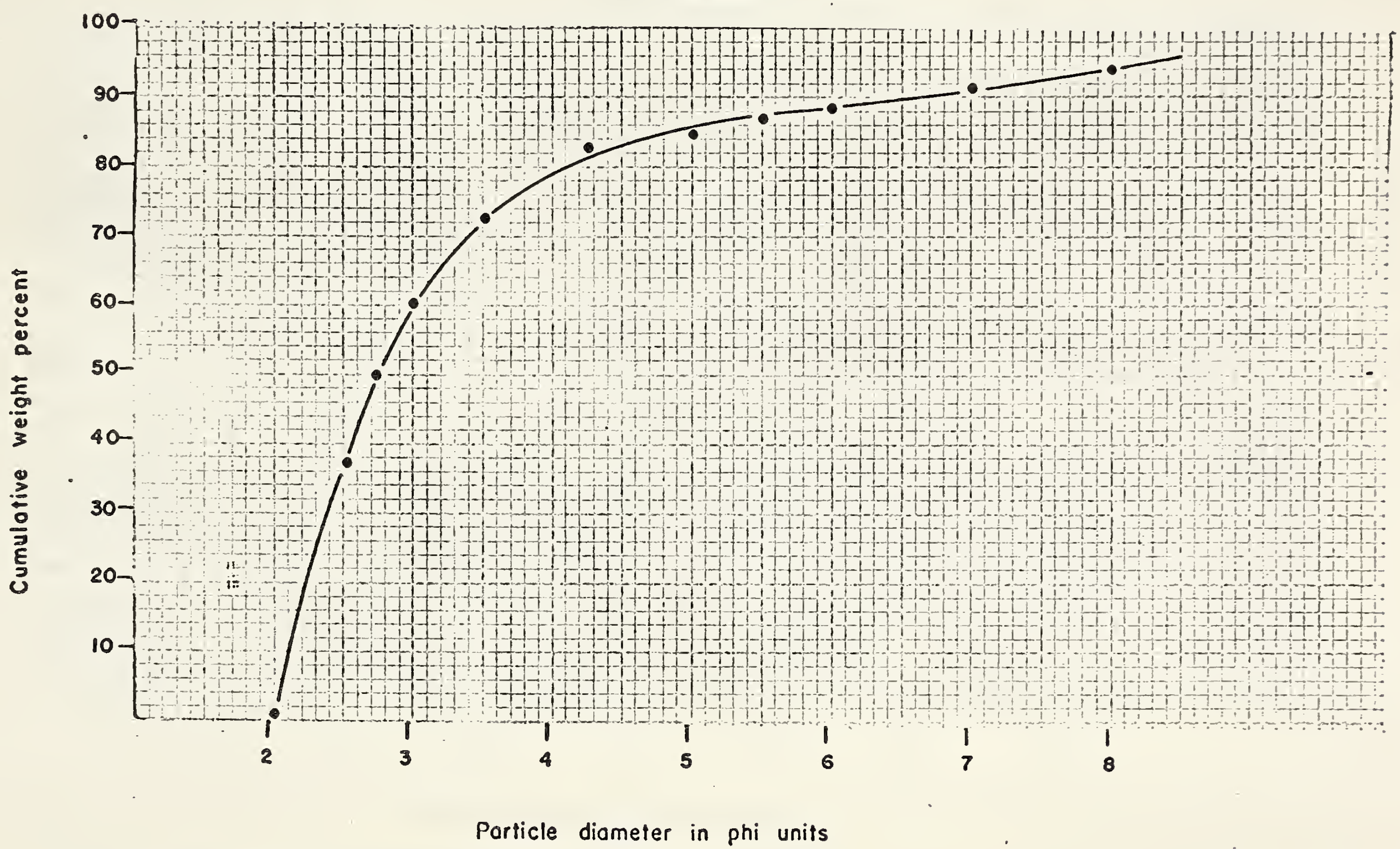
Cumulative Curve



Particle diameter in phi units

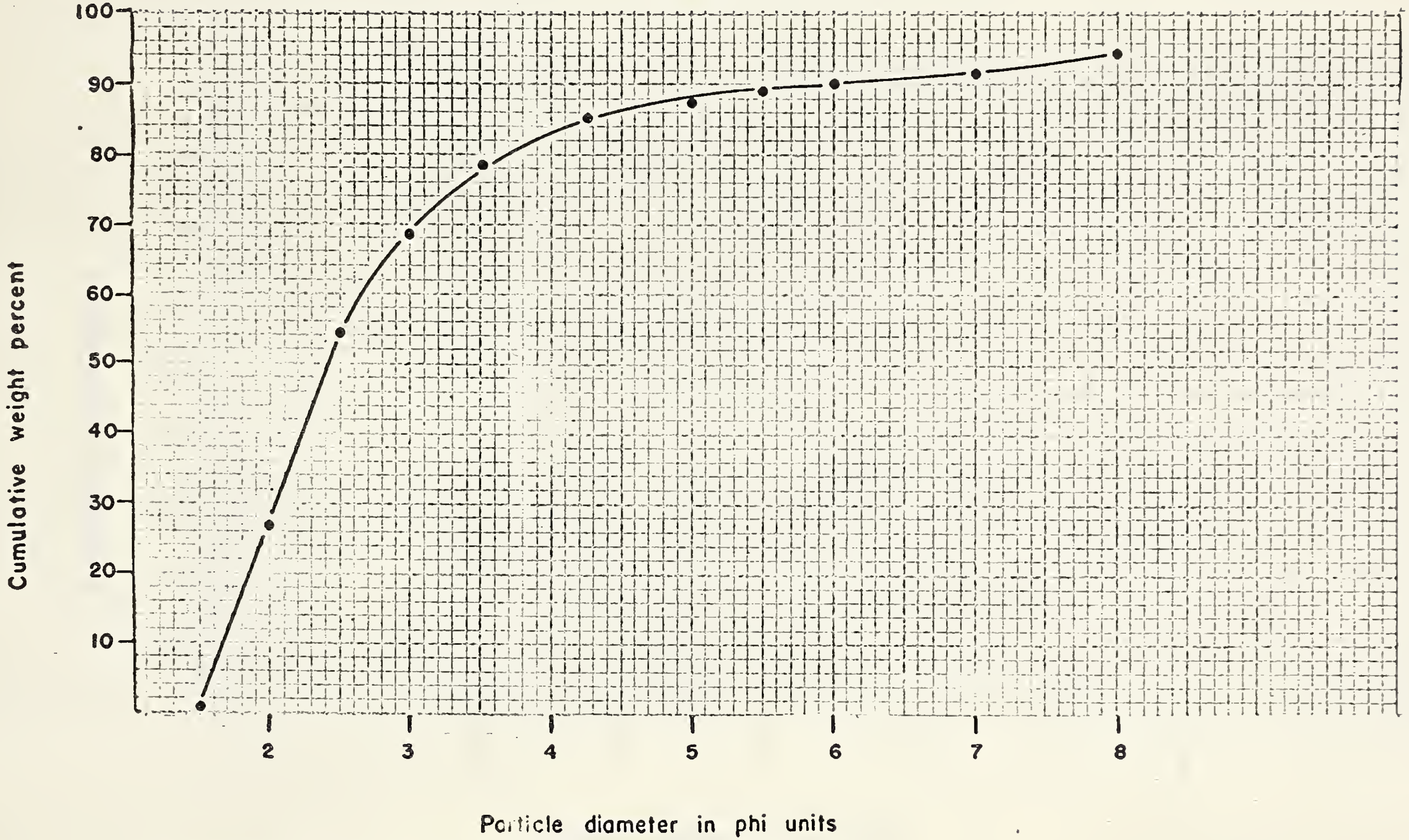
Whitehall et al Keystone 6-3
Lsd.6, Sec.3, Twp.48, Rge.3 W5M.
Depth 3197 feet

Cumulative Curve



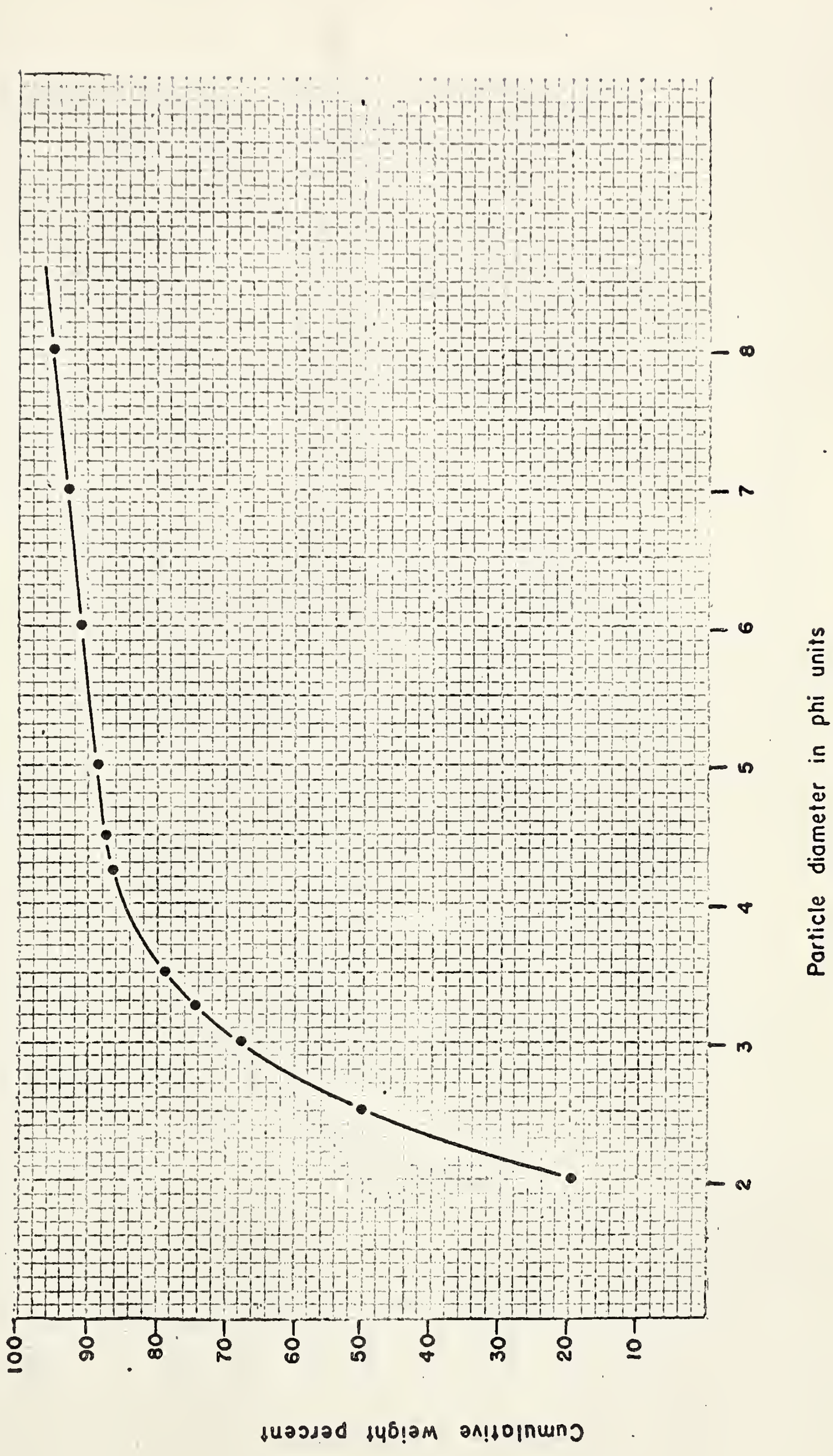
Whitehall et al Keystone 6-3
Lsd.6, Sec.3, Twp.48, Rge.3 W5M.
Depth 3202.5 feet

Cumulative Curve



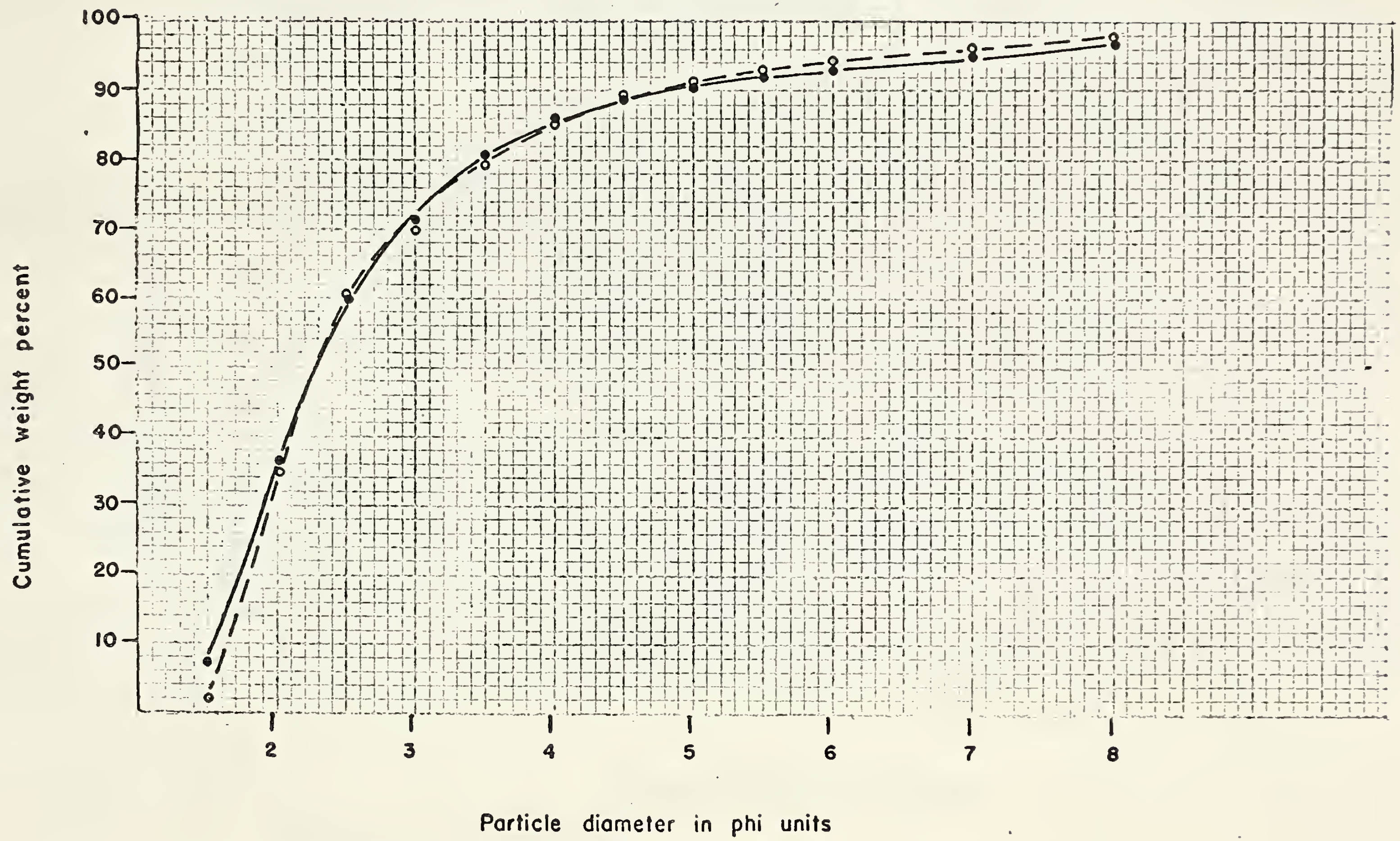
Whitehall et al Keystone 6-3
Lsd.6, Sec.3, Twp.48, Rge.3 W5M.
Depth 3207 feet

Cumulative Curve



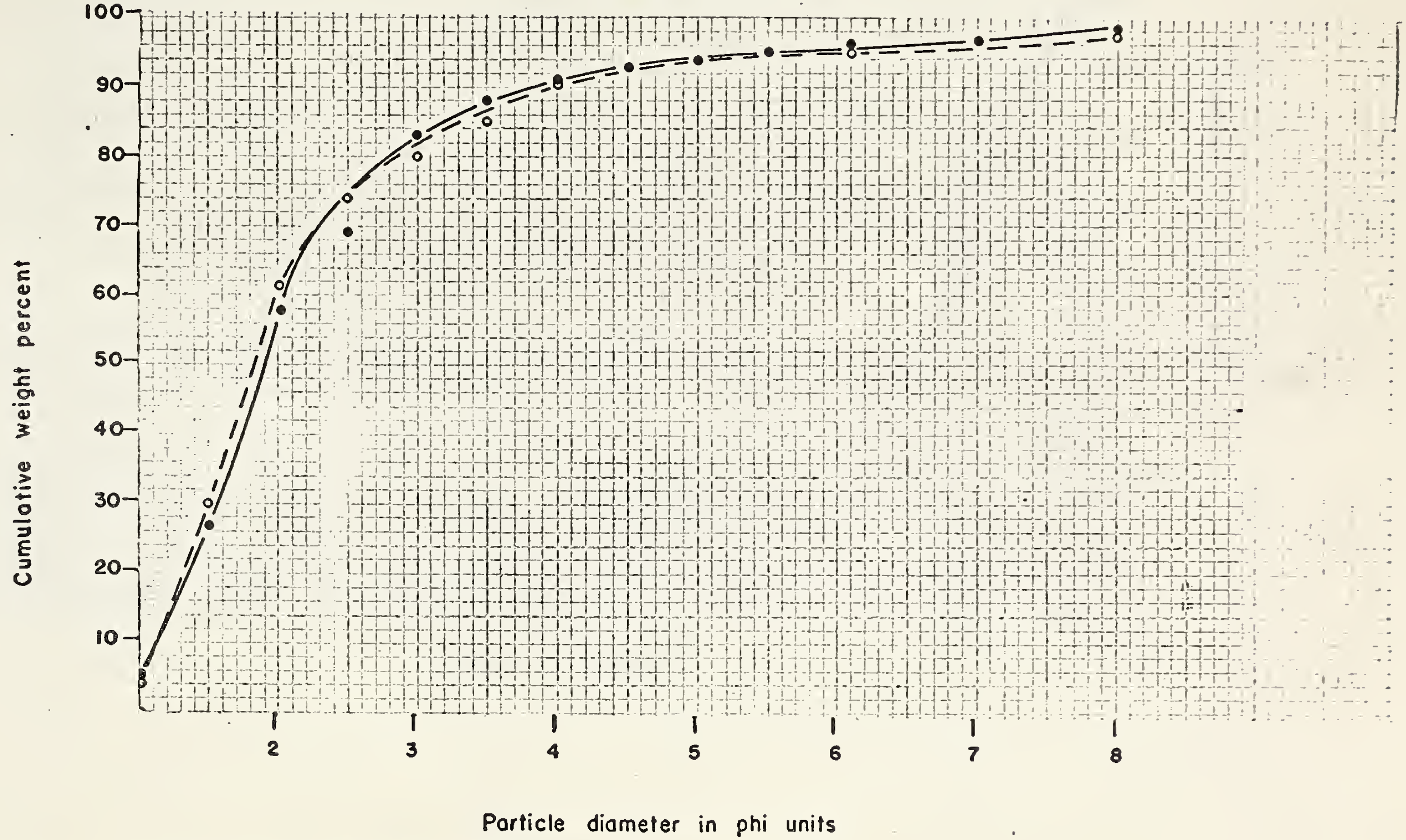
Whitehall et al Keystone 6-3
Lsd.6, Sec.3, Twp.48, Rge.3 W5M.
Depth 3214.5 feet

Cumulative Curve

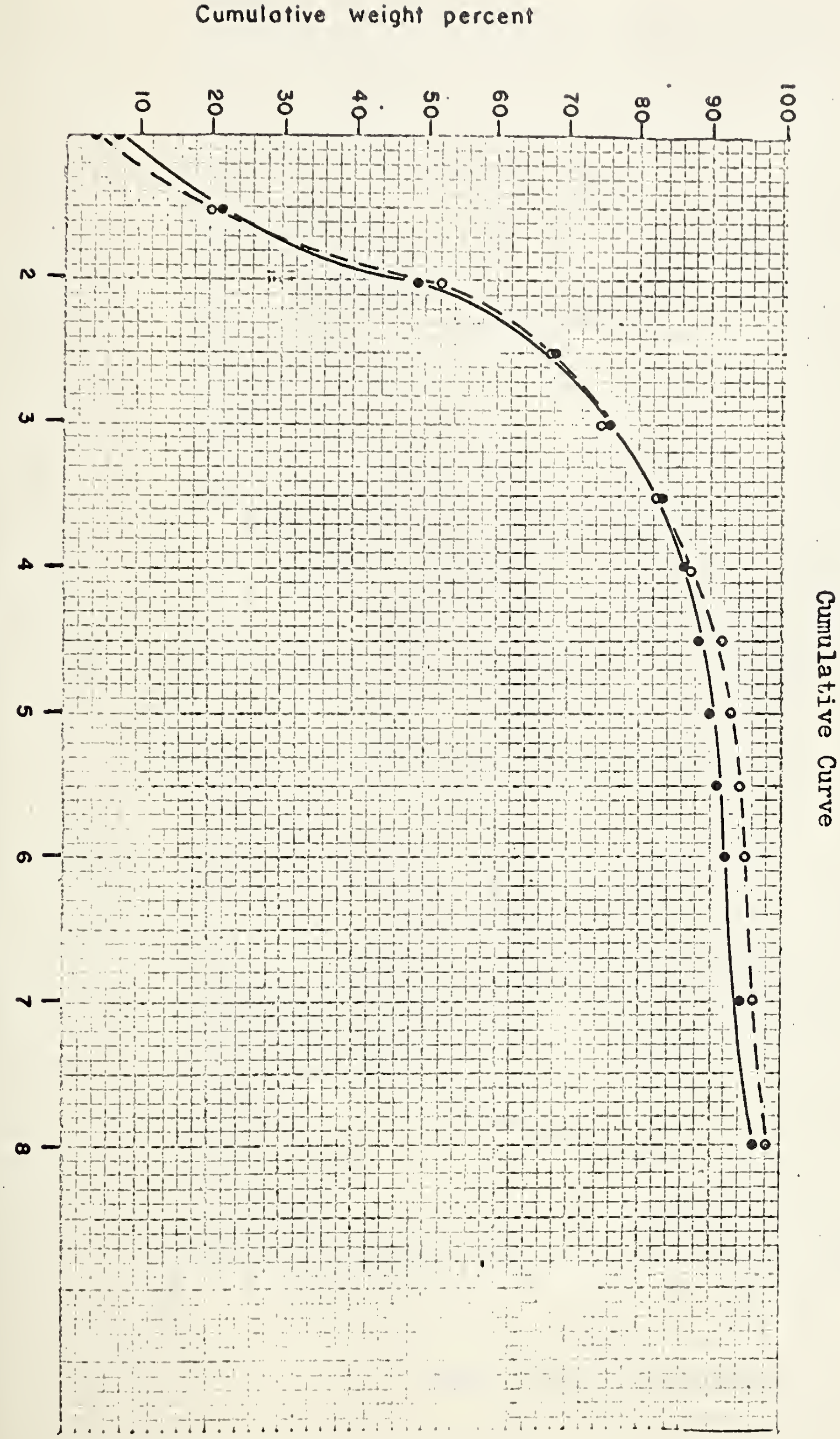


Whitehall Keystone 14-9
Lsd.14, Sec.9, Twp.48, Rge.3W5M.
Depth 3061.5 feet

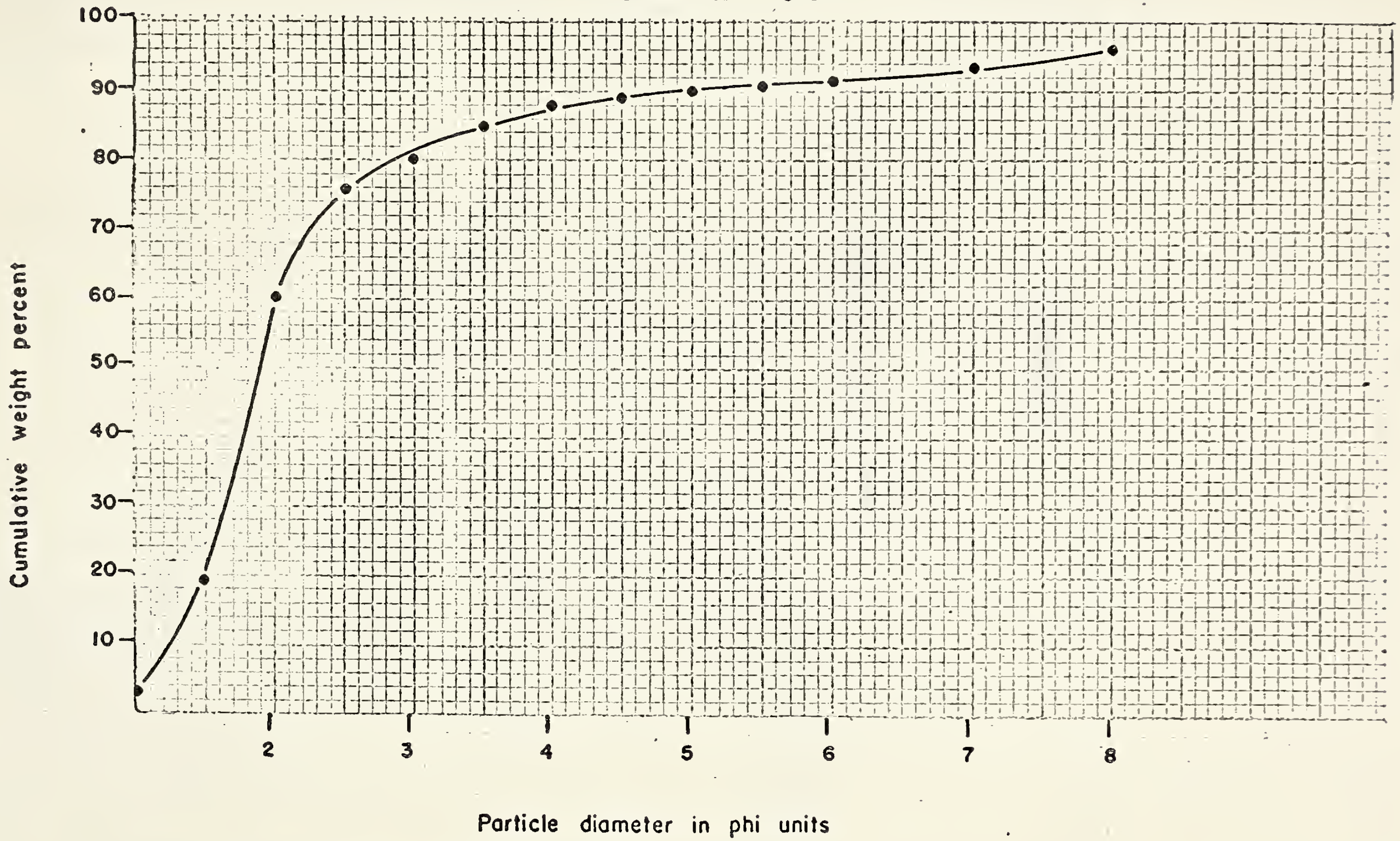
Cumulative Curve



Whitehall Keystone 14-9
Lsd.14, Sec.9, Twp.48, Rge.3 W5M.
Depth 3074 feet


Cumulative Curve
Cumulative weight percent
10
20
30
40
50
60
70
80
90
100
Particle diameter in phi units
2
3
4
5
6
7
8

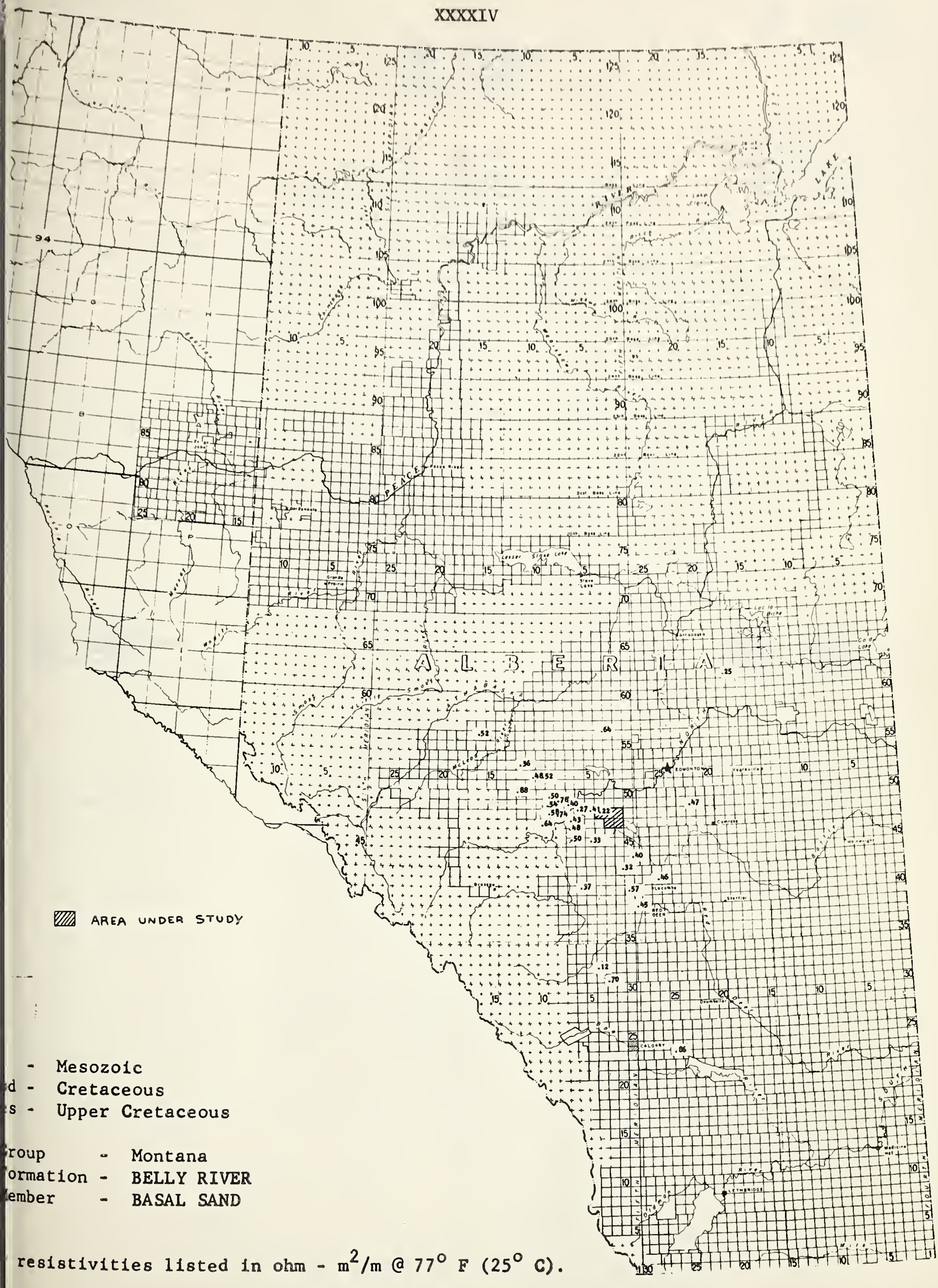
Cumulative Curve



Imperial Canadian Superior Berrymoor 8-4C
Lsd.8, Sec.4, Twp.49, Rge.6 W5M.
Depth 2425 feet

APPENDIX G

FORMATION WATER DATA



- Mesozoic
d - Cretaceous
s - Upper Cretaceous

roup - Montana
ormation - BELLY RIVER
ember - BASAL SAND

resistivities listed in ohm - m^2/m @ 77° F (25° C).

(After Schlumberger, 1962)

ERA Cenozoic
PERIOD Tertiary
SERIES Eocene & Paleocene
GROUP
FORMATION Paskapoo

1.	16 - 35 - 47 - 8 W 5	9.9
2.	8 - 27 - 47 - 9 W 5	7.0
3.	16 - 33 - 48 - 8 W 5	10.
4.	16 - 14 - 48 - 9 W 5	9.0
5.	2 - 24 - 48 - 10 W 5	8.4
6.	14 - 3 - 49 - 9 W 5	11.

ERA Mesozoic
PERIOD Cretaceous
SERIES Upper Cretaceous
GROUP Montana
FORMATION Edmonton
(St. Mary R., Bearpaw)

1.	1 - 34 - 47 - 8 W 5	8.7
2.	10 - 18 - 51 - 8 W 5	1.2

ERA Mesozoic
PERIOD Cretaceous
SERIES Upper Cretaceous
GROUP Montana
FORMATION Belly River
MEMBER Basal Sand

1.	6 - 29 - 23 - 25 W 4	.86
2.	6 - 28 - 38 - 28 W 4	.45
3.	1 - 22 - 41 - 26 W 4	.46
4.	14 - 5 - 49 - 22 W 4	.47
5.	10 - 14 - 62 - 18 W 4	.25
6.	11 - 6 - 31 - 3 W 5	.70
7.	11 - 18 - 32 - 4 W 5	.12
8.	14 - 16 - 40 - 1 W 5	.57
9.	12 - 27 - 40 - 6 W 5	.37
10.	11 - 25 - 42 - 2 W 5	.52
11.	10 - 36 - 43 - 1 W 5	.40
12.	4 - 22 - 45 - 5 W 5	.35
13.	6 - 26 - 45 - 7 W 5	.50
14.	12 - 32 - 46 - 7 W 5	.48
15.	10 - 27 - 47 - 7 W 5	.43
16.	16 - 10 - 47 - 9 W 5	.64
17.	14 - 22 - 48 - 4 W 5	.22
18.	6 - 27 - 48 - 5 W 5	.41
19.	14 - 29 - 48 - 6 W 5	.27
20.	8 - 20 - 48 - 6 W 5	.33
21.	12 - 12 - 48 - 8 W 5	.74
22.	14 - 17 - 48 - 9 W 5	.58
23.	8 - 4 - 49 - 6 W 5	.35
24.	10 - 8 - 49 - 7 W 5	.40
25.	6 - 17 - 49 - 7 W 5	.54
26.	6 - 29 - 49 - 8 W 5	.78
27.	16 - 8 - 49 - 9 W 5	.54
28.	8 - 5 - 50 - 9 W 5	.50
29.	12 - 30 - 50 - 12 W 5	.88
30.	15 - 2 - 52 - 10 W 5	.52
31.	3 - 1 - 52 - 11 W 5	.48
32.	11 - 16 - 53 - 12 W 5	.36
33.	6 - 36 - 56 - 4 W 5	.64
34.	14 - 20 - 56 - 16 W 5	.52

ERA Mesozoic
PERIOD Cretaceous
SERIES Upper Cretaceous
GROUP Colorado
FORMATION Medicine Hat SS

1.	5 - 34 - 10 - 7 W 4	.42
2.	11 - 11 - 11 - 2 W 4	.47
3.	1 - 16 - 11 - 11 W 4	1.3
4.	11 - 14 - 12 - 2 W 4	.37

ERA Mesozoic
PERIOD Cretaceous
SERIES Upper Cretaceous
GROUP Colorado
FORMATION Cardium

1.	16 - 20 - 56 - 16 W 5	.23
2.	9 - 9 - 62 - 26 W 5	.60
3.	11 - 11 - 68 - 3 W 6	.11

(After Schlumberger, 1962)

-1

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ANALYTICAL LABORATORY
in cooperation with
Department of Chemical & Petroleum Engineering
University of Alberta

Engineering Building,
University of Alberta,
Edmonton, Alberta.

REPORT OF ANALYSIS

aboratory Order and Report Number E 18789 Date of Report

Date of Analysis Feb. 2, 1962

Date of Sampling Jan. 28, 1962

ell Name and Number Calstan Pembina 6-34 mu -47-2

ell Location LSD 6 Sec. 34 Twp. 47 Rge. 2 West 5 Mer.

eld or Area Pembina Pool Pembina B.R. "m" Pool

mple obtained from Drill pipe Method of Production D.S.T. #1

ST Recovery 70' oil, 50' oil and mud, 110' oil flaked muddy water

epth interval sampled 3271 feet to 3312 feet. K.B. Elevation 3007' Grd. 2993 feet

me of zone and formation sampled Basal Belly River Top Bottom

mple obtained by (individual)

The California Standard Company (organization)

ANALYSIS OF RESERVOIR WATER

pearance of Sample:

	Mg per liter (ppm)	Percent of Calculated Solids
	500	25.9
$_3$	64	3.3
CO_3	497	25.8
$_4$	211	10.9
	9	0.5
	3	0.2
* (calc)	645	33.4
al Solids calc.)	1,929	100.0

Density, 60° F.	1.010
pH	8.6
H_2S	-
Resistivity ohm-meters, ~~25° C~~.	60°F = 2.69
Ref. Index, 25° C.	13360
Total Solids evap. at 110° C.	2,156
evap. at 180° C.	
evap. at ° C.	
after ignition	1,676

*Alkali metals calculated as Na.

marks: This sample is a mud filtrate:

Primary salinity	64.26	Secondary Alkalinity	2.44
Secondary Salinity	-	Chloride Salinity	76.25
Primary Alkalinity	33.30	Sulphate Salinity	23.75

lyzed by: Chemical & Geological Labs.Ltd. Approved by:

ies to:

L-1

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Edmonton, Alberta.

REPORT OF ANALYSIS

Laboratory Order and Report Number CBH-2-WA-1639 Date of Report

Date of Analysis March 16, 1962

Date of Sampling March 9, 1962

Well Name and Number Suptst Pembina 8-4BR -48 -2

Well Location LSD 8 Sec. 4 Twp. 48 Rge. 2 West 5 Mer.

Field or Area Pembina Pool Pembina Keystone Belly River "M"

Sample obtained from At tool Method of Production D.S.T. #1

DST Recovery Mud-oil-water emulsion

Depth interval sampled 3064 feet to 3108 feet. K.B. Elevation feet

Name of zone and formation sampled Belly River Top Bottom

Sample obtained by Supertest Pet. Corp. (individual)

(organization)

ANALYSIS OF RESERVOIR WATER

Appearance of Sample:

	Mg per liter(ppm)	Percent of Calculated Solids
Cl	1,011	
CO_3		
HCO_3		
SO_4		
OH		
F		
Ca		
Mg		
Na* (calc)		
Total Solids (calc.)		

Density, 60° F.	
pH	
H_2S	
Resistivity 72 °F ohm-meters, ~~25° C.~~	1.5
Ref. Index, 25° C.	
Total Solids evap. at 110° C.	
evap. at 180° C.	
evap. at ° C.	
after ignition	

*Alkali metals calculated as Na.

Remarks: See back of sheet

Analyzed by: Core Labs. - Canada Ltd. Approved by:

Copies to:

Same well:

CBH-2 -WA-1639(2)	DST #1 (at 120') Belly River
	Resistivity - 1.6 @ 72°F
	Chloride - 1,058 ppm.
	Complete analysis not feasible.
CBH-2 -WA-1639(3)	Glass bottle sampled by client.
	Belly River.
	Resistivity - 1.6 @ 72°F
	Chloride - 1,079 ppm.
	Complete analysis not feasible.

-1

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REPORT OF ANALYSIS

Laboratory Order and Report Number W21-254 Date of Report

Date of Analysis Jan. 17, 1955

Date of Sampling Dec. 14, 1954

Well Name and Number Texaco Socony Warburg A2-2

Well Location LSD 2 Sec. 28 Twp. 48 Rge. 2 West 5 Mer.

Field or Area Pool

Sample obtained from Drill pipe Method of Production DST #2

DST Recovery 150' oil cut mud, 180' mud cut oil, and 520' fresh water

Depth interval sampled 2862 feet to 2902 feet. K.B. Elevation feet

Name of zone and formation sampled Top Bottom

Sample obtained by D. Mackinnon, Texaco Exploration Co. (individual)

(organization)

ANALYSIS OF RESERVOIR WATER

Appearance of Sample: A thin layer of sediment on the bottom of the jar. Colorless and murky water.

	Mg per liter (ppm)	Percent of Calculated Solids
Cl	1,849	59.0
CO_3		
HCO_3 (est.)	500	
SO_4 (est.)	500	
OH		
r		
a + mg (as Ca)	176	0.9
g		
Na* (calc)		
Total Solids (calc.)		

*Alkali metals calculated as Na.

Density, 60° F.	1.018
pH	7.6
H_2S	None
Resistivity ohm-meters, 25° C.	0.337 ohm.m.
Ref. Index, 25° C.	1.3361
Total Solids evap. at 110° C.	
evap. at 180° C.	
evap. at ° C.	
after ignition	19,000

Remarks:

Analyzed by: University of Alberta Approved by:

Copies to:

.-1

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REPORT OF ANALYSIS

aboratory Order and Report Number CNP-1-WA-12 Date of Report

Date of Analysis April 9, 1959

Date of Sampling April 8, 1959

Vell Name and Number Cities Service Keystone 14-22-48-4

Vell Location LSD 14 Sec. 22 Twp. 48 Rge. 4 West 5 Mer.

ield or Area Pembina Pool Keystone Belly River "A"

ample obtained from Sample of water while flowing Method of Production

ST Recovery

epth interval sampled 3252 feet to 3264 feet. K.B. Elevation feet

ame of zone and formation sampled Basal Belly River Top Bottom

ample obtained by Canada - Cities Service Pet. Corp. (individual)

(organization)

ANALYSIS OF RESERVOIR WATER

ppearance of Sample:

	Mg per liter (ppm)	Percent of Calculated Solids
l	16,685	57.0
O_3		
CO_3	34	0.1
O_4	1,978	6.7
H		
r		
a	2,000	6.8
g	996	3.4
a* (calc)	7,613	26.0
tal Solids (calc.)	29,306	100.0

*Alkali metals calculated as Na.

Density, 60° F.	1.0206
pH	5.75 @ 20°C
H_2S	Absent
Resistivity ohm-meters, 25° C.	0.25 @ 77°F
Ref. Index, 25° C.	or 0.30 @ 64°F
Total Solids evap. at 110° C.	
evap. at 180° C.	
evap. at ° C.	
after ignition	

marks: Hypothetical combination -

Calcium Chloride	5,540 ppm.	Sodium Chloride	16,965
Magnesium Bicarbonate	41 ppm.	Sodium Sulfate	2,911
Magnesium Chloride	3,848 ppm.		

alyzed by: Core Labs. - Canada Ltd. Approved by:

pies to:

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Edmonton, Alberta.

REPORT OF ANALYSIS

aboratory Order and Report Number L- 41857 Imp. oil ltd. Date of Report ....

Date of Analysis July 26, 1957

Date of Sampling ....

Vell Name and Number Imperial Breton 6-33C - 48-4

Vell Location LSD 6 Sec. 33 Twp. 48 Rge. 4 West 5 Mer.

ield or Area Keystone Pool ....

ample obtained from DST #2 Method of Production ....

ST Recovery 2000/mcf, 230' of gasy oil, 30' oil cut mud

epth interval sampled 3270 feet to 3310 feet. K.B. Elevation 2832 feet

ame of zone and formation sampled Buck Creek and Lea Park Top .... Bottom ....

ample obtained by .... (individual)

.... (organization)

ANALYSIS OF RESERVOIR WATER

ppearance of Sample:

	Mg per liter (ppm)	Percent of Calculated Solids
	184	8.7
O_3	120	5.7
CO_3	744	35.1
O_4	389	18.4
H	-	-
	4	0.2
g	-	-
* (calc)	674	31.9
tal Solids (calc.)	2,115	100.0

*Alkali metals calculated as Na.

Density, 60° F.	Insufficient sample
pH	8.94
H_2S	Nil
Resistivity ohm-meters, 25° C.	
Ref. Index, 25° C.	
Total Solids evap. at 110° C.	
evap. at 180° C.	
evap. at ° C.	
after ignition	

marks: Sample from top of fluid

a = 49.7 Primary Salinity = Alkali Salinity = 45.0

b = 0.3 Primary Alkalinity = Permanent Alkalinity = 54.4

c = 22.5 Secondary Alkalinity = Temporary Alkalinity = 0.6

100.0

alyzed by: .... Approved by: ....

pies to: ....

APPENDIX H

DERIVATION OF FORMATION WATER RESISTIVITY

DERIVATION OF FORMATION WATER RESISTIVITY

When direct resistivity measurements are not available on a sample but where chemical water analysis from a representative formation sample has been made, a reliable value for the resistivity may be computed.

A method worked out by the Atlantic Refining Company Laboratories has proved very dependable for this purpose. The concentration of each ion in parts per million (ppm) is reduced to equivalent NaCl salinity by means of conversion factors. The equivalent NaCl salinity is then entered into the Schlumberger Chart A6 to determine the resistivity at the desired temperature. An example from the water analysis data of the Cities Service Keystone 14-22 well (Lsd. 14, Sec. 22, Twp. 48, Rge. 4 W5M.) is given below to illustrate the method:

TABLE

Ions	ppm	Conversion Factor	Equivalent NaCl Salinity
Cl^-	16,685	1.00	16,685
$HCO3^-$	34	0.27	9
SO_4^{--}	1,978	0.50	989
Ca^{++}	2,000	0.95	1,900
Mg^{++}	996	2.00	1,992
Na^+	7,613	1.00	7,613

Total = 29,188 ppm

Using Schlumberger Chart A6 ; Rw = 0.25 ohm m @ 64°F

If the water analysis is available only as a function of the Palmer method of representation, the equivalent NaCl salinity may also be obtained by a similar method through the use of the conversion factors as shown below. The same well is used for illustration.

TABLE

Palmer Salts	ppm	Conversion Factor	Equivalent NaCl Salinity
Primary salinity ($NaCl$)	16,965	1.00	16,965
Primary salinity ($Na_2 SO_4$)	2,911	0.40	1,164
Secondary salinity ($CaCl_2$, $MgCl_2$)	9,388	0.37	3,465
Secondary alkalinity ($Mg (HCO_3) 2$)	41	0.27	15

Total = 21,609

Using Schlumberger Chart A6 ; Rw = 0.33 ohm m @ $64^{o}F$

<u>Determination of Rw from direct measurement on a representative sample</u>

Measurement of formation water resistivity is made directly in the laboratory at a standard temperature by means of a conductivity dip cell and results reported directly in ohm meters.

APPENDIX I

DETERMINATION OF SPONTANEOUS POTENTIAL LITHOLOGIC FACTOR (K)

DETERMINATION OF LITHOLOGICAL FACTOR (K)

Measurements made by a thermometer lowered in a drill hole give the temperature of the drilling mud. Unless the hole has not been circulated for several weeks, the temperature of the mud is different from that of the formation. The mud is usually colder at the bottom and hotter at the top of the hole than is the surrounding strata.

In the area under consideration, no open hole temperature surveys were run in wells reaching Basal Belly River sandstone and deeper.

Most of the temperature surveys were run after the casing was lowered and cemented in order to locate the top of cement behind casing. Such temperature logs are of no use in determining the formation temperature. However, bottom hole temperatures were recorded on the conventional electrical logs in a few wells (listed below) which bottomed near the base of the Basal Belly River sandstone. As mentioned above, these are not genuine formation temperatures, since they were recorded only two to three hours after the circulation was stopped. However, with available data, an average geothermal gradient of $1.59^{o}F/100$ feet was estimated (Table, pp. LVI). This is slightly higher than the gradient of $1.26^{o}F/100$ feet found by Vladica (1957) in the Sundre oil-field in east central Alberta.

TABLE

Well location	Max.recorded B.H.T.^{o}F	Total depth	Effective depth	Base of Bsl. Belly River sandstone	Geothermal Gradient/100 feet	Remark
6- 6-48-2W5	86	3261	3161	3242	1.29	Geothermal Gradient based on 45^{o}F as a mean annual temperature at 100 feet from the surface below which no seasonal variations exist (Vladica,1957)
14-21-48-2W5	88	2920	2820	2921	1.52	
8-31-47-2W5	96	3365	3265	3366	1.56	
14-33-47-2W5	96	3247	3147	3224	1.62	
8-34-47-2W5	96	3371	3271	3322	1.56	
14-34-47-2W5	97	3222	3122	3178	1.66	
14-35-47-2W5	96	3234	3134	3206	1.63	

Average Geothermal Gradient = 1.59^{o}F/100 feet

In the present study, the formation temperature of the basal Belly River sandstone was taken as approximately 96^{o}F or 35.5^{o}C. The value of K corresponding to this temperature is 73 (Slack and Otte,1960).

APPENDIX J

LEAST SQUARES POWER SERIES ANALYSIS

LEAST SQUARE POWER SERIES ANALYSIS

The brief theory of least square power series analysis is given here mainly to define certain terms needed for interpretation of analytical results. The discussion here refers to analysis of maps of any scale with any arrangement of control points from purely random to varying degree of regularity or clustering. The analysis is based upon conventional least squares methods for fitting the linear, the quadratic and the cubic surface to the observed data. Solution of the resulting simultaneous equations is carried out in matrix form. Let U be the north-south coordinate and V as the east-west coordinate and let X_{ij} be a single observation of the mapped variable at coordinates (U_i, V_j). Then a polynomial trend surface in the two variables U and V may be expressed as

$$t = f(U,V) = A_{00} + A_{10}U + A_{01}V + A_{20}U^2 + A_{11}UV + \ldots . A_{pq}U^pV^q \ldots . . (1)$$

where t is the trend as estimated from a polynomial of degree (p,q) that best fits the observed data. The A's in the equation (1) are estimates of the polynomial coefficients.

The computed value of the trend surface for some given point (U,V) differs from the observed X at the same point by a residual ϵ that represents the small scale fluctuations, deviations between the true surface and its assumed form and observational errors. That is in the present notation

$$X_{ij} = t_{ij} + \epsilon_{ij}$$

The equation for a linear surface at the point (U,V) represented by the first three terms on the right hand side of equation (1) may be

expressed more simply as

$$Y(U,V) = a + bU + CV$$

Here $Y(U,V)$ is the trend value of the linear surface at point (U,V) and a, b, and c are the linear coefficients. Let $Y(U_i,V_j)$, the trend value at the observation point X_{ij}, be denoted as Y_{ij}. The deviations from the linear surface $(X_{ij} - Y_{ij})$ now represent non-linearities of the surface as well as observational errors. The deviations may be designated as R_{ij} so that $X_{ij} = Y_{ij} + R_{ij}$.

For least squares fit of the linear surface, the sum of squares of the deviations $R = X - Y$, which is a function of a, b and c only (Hoel, 1947, p. 90), is minimized.

$$\Sigma R^2 = G(a\ b,c)$$

$$= \Sigma(X - a - bU - cv)^2$$

To minimize $G(a,b,c)$ requires that the partial derivatives be set to zero.

$$\partial G/\partial a = \Sigma 2\ (X - a\text{-}bU - cV)\ (-\ 1) = 0$$

$$\partial G/\partial b = \Sigma 2\ (X - a - bU - cV)\ (-\ U) = 0$$

$$\partial G/\partial c = \Sigma 2\ (X - a - bU - cV)\ (-\ V) = 0$$

Multiplication of each expression and summation over the individual terms yields three normal equations. These are

$$aN + b\ \Sigma U + C\ \Sigma V = \Sigma X$$

$$a\Sigma U + b\ \Sigma U^2 + C\ \Sigma UV = \Sigma UX$$

$$a\Sigma V + b\ \Sigma UV + c\ \Sigma V^2 = \Sigma VX$$

Calculation of the coefficients in these normal equations and the subsequent solution is conveniently handled on high speed computers. When expressed in matrix form, these equations are:

$$\begin{bmatrix} N & \Sigma U & \Sigma V \\ \Sigma U & \Sigma U^2 & \Sigma UV \\ \Sigma V & \Sigma UV & \Sigma V^2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \Sigma X \\ \Sigma UX \\ \Sigma VX \end{bmatrix}$$

The (U,V) matrix and column vector (X) are set up from the observational data. The coefficient vector is obtained by taking the inverse of the (U,V) matrix, $(U,V)^{-1}$, and post-multiplying it by the (X) column vector.

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = [U,V]^{-1} \; [X]$$

The coefficients a b, and c are used to compute Y_{ij} for the linear surface at the control points on the map and the map of deviations from the linear surface can be had from $X_{ij} - Y_{ij}$.

If a quadratic surface is required, the program calculates the 6 x 6 [U,V] matrix and [X] column vector. Similarly for a cubic surface the program calculates the 10 x 10 [U,V] matrix and [X] column vector for the complete cubic surface. These are punched as the linear 3 x 3 matrix and its column vector, the 6 x 6 quadratic matrix and its column vector, and the 10 x 10 cubic matrix and its column vector.

The matrices are inverted individually and are then used with their column vectors to obtain the sets of linear, quadratic and cubic coefficients.

Initially, an eight digit floating point mantissa as employed by Krumbein (1959) was used but due to the ill-conditioning of the [U,V] matrix, it was necessary to resort to a 20 digit mantissa to obtain correct coefficients.

An arbitrary geographic coordinate system was established so that each locality is described by two coordinate values, namely U and V. The center of the coordinate system was chosen at O, which is the

south-west corner of the township 47, and Range 4. Each well in a legal subdivision is considered to be at its centre. Consider the Cities Service Keystone 14-16 well (Lsd. 14, Sec. 16, Twp. 48, Rge. 4 W5 Mer.). The coordinates of the well, under consideration, are 2.375 and 8.875 miles respectively. Suppose, we want to calculate the value of the quadratic surface (the trend t) at this point using the quadratic coefficients calculated by the computer. To obtain t, the polynomial coefficients A_{100}, A_{10}, A_{01}, A_{20}, A_{11} and A_{02} in the quadratic equation

$$t = A_{00} + A_{10}U + A_{01}V + A_{20}U^2 + A_{11}UV + A_{02}V^2$$

are necessary. The polynomial coefficients, calculated by the computer, which when substituted in the above equation, results in

$$t = 498.16$$

The deviation from the quadratic surface (residual on the trend) is the observed value minus the calculated value i.e.

$$481.00 - 498.16 = - 17.16$$

which is also printed out along with the trend value.

In a similar fashion, the values of the linear and cubic surfaces and the deviations from them were calculated.

The variation of a set of observations from the polynomial surfaces (i.e. linear, quadratic or cubic) may be measured by the sum of squares of the deviations for a fixed number of observation points. Following the calculation of trend and residual values, the program calculated the sum of squares of residuals on the linear, quadratic and cubic surfaces for a fixed total of 187 observation points.

APPENDIX K

COMPUTER PROCEDURE FOLLOWED

COMPUTER PROCEDURE FOLLOWED

DATA INPUT

An example from Cities Service Keystone 16-14 well (Lsd. 16, Sec. 14, Twp. 48, Rge. 4 W5 Mer.) illustrates the different picks made from the log with respective codes (Figure 3).

Apart from various markers picked, shale intervals greater than 1 foot within the basal Belly River sandstone were recorded. Also recorded was the spontaneous potential against the sandstone in the bore hole, and the resistivities of the mud, mud filtrate and mud-cake with their temperatures of measurement.

The mud resistivity and mud-cake resistivity were, however, not punched on the input cards.

The well location was codified by four letters, J, K, L and M preceded by the letter I representing the serial number of the well.

Category	Code	Explanation
Well location:	I	Serial number
	J	Legal sub-division
	K	Section
	L	Township
	M	Range and Meridian (under M, 'W' is replaced by '0' i.e., read 3W5 instead of 305)
Stratigraphic picks:	COLRT	Top of Colorado/First White Specks
	TMLKR	Marker in Lea Park Shale
	BELRT	Top of basal Belly R. Sandstone
	BELRB	Bottom of basal Belly R. Sandstone
	Shale intervals between BELRT and BELRB	
	SHLT 1	Top of first shale
	SHLB 1	Bottom of first shale
	SHLT 2	Top of second shale
	SHLB 2	Bottom of second shale
	SHLT 3	Top of third shale
	SHLB 3	Bottom of third shale
	SHLT 4	Top of fourth shale
	SHLB 4	Bottom of fourth shale
	SHLT 5	Top of fifth shale
	SHLB 5	Bottom of fifth shale

	COAL 1	Bottom of first coal
	COAL 2	Bottom of second coal
<u>Miscellaneous</u>	ELKB	Kelly Bushing elevation
	E 1	Spontaneous potential against basal Belly River Sandstone
	RFM	Resistivity of mud filtrate
	TEMP	Temperature of measurement of RFM

All the above data picked from the well log were first tabulated and then punched on cards from the tabulated sheets. The data from each well were punched on three cards as shown in Figure 39.

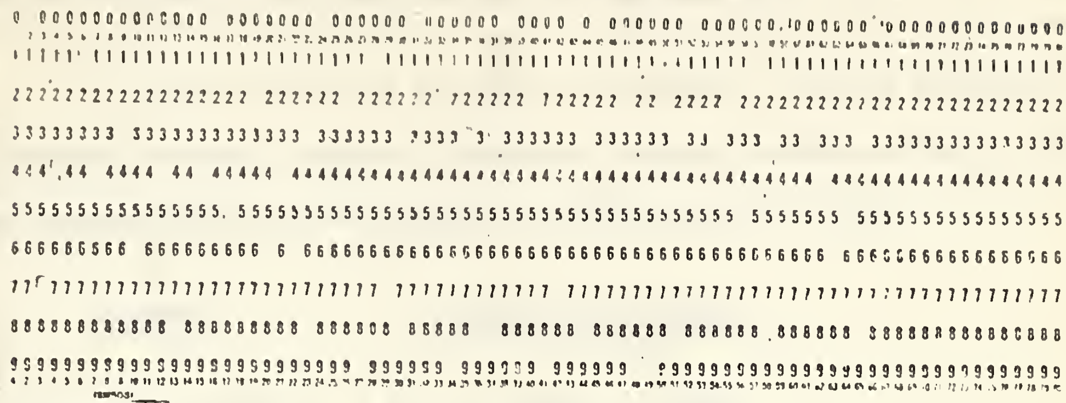
The input data for a computer must be given in a certain sequence or format. A format is simply the way in which the input data are arranged on the punched cards column by column and card by card. In this program, the first 17 columns of card 1 contain the serial number and the well location which in turn are followed by the Kelly Bushing elevation, and depths to markers COAL 1, COAL 2, BELRT, BELRB, TMLKR, and COLRT covering a total of 66 columns in the card. On card 2, the same well identification again occupies the first 17 columns which in turn are followed by depths to SHLT 1, SHLB 1, SHLT 2, SHLB 2, SHLT 3, SHLB 3, and SHLT 4, occupying a total of 66 columns. Card 3 repeats the well identification followed by depths to SHLB 4, SHLT 5 SHLB 5 and E 1, RFM and TEMP.

Wherever the input data were not available or difficult to pick from the well logs, zeros were punched instead.

In this study, the programming was done in four parts and the Fortran language was used in all.

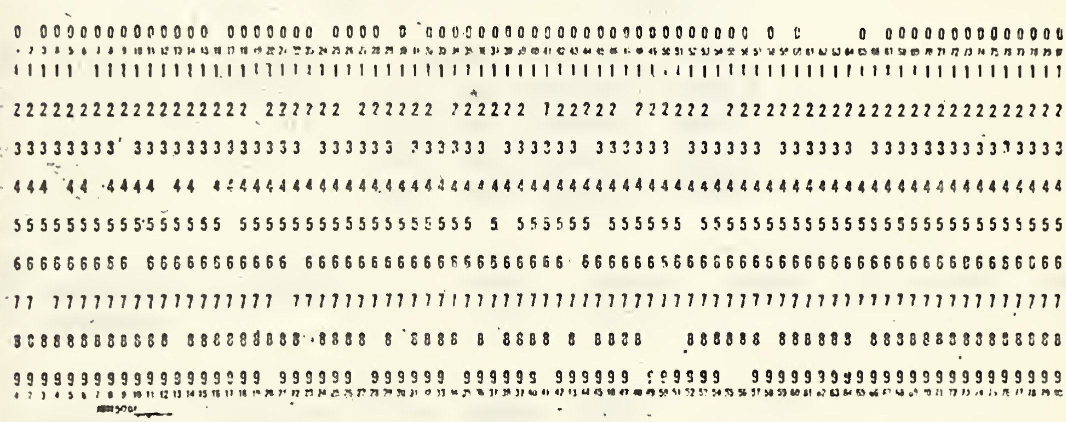
INPUT CARD FORMAT

074	14	36	48	405	2646.0	2917.0	2938.0	2970.0	2992.0	3251.0	3465.0
	WELL LOCATION										
I	J	K	L	M	ELKB	COAL1	COAL2	BELRT	BELRB	TMLKR	COLRT



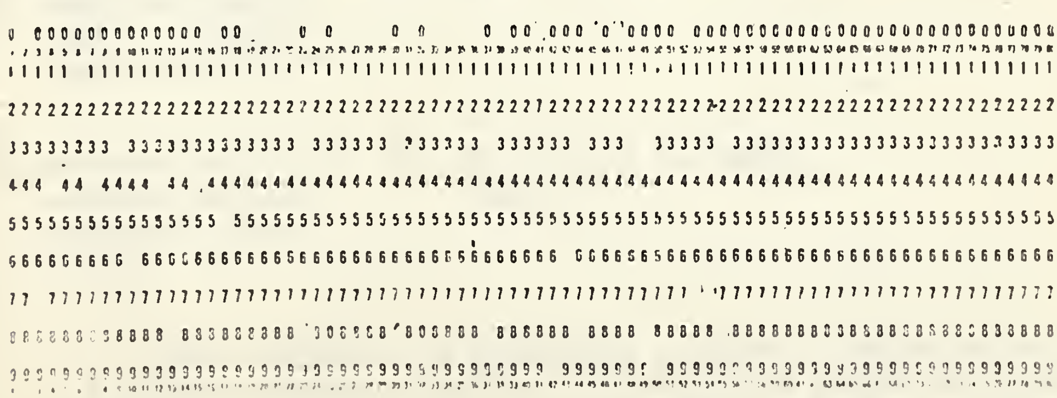
CARD 1

074	14	36	48	405	2976.0	2980.0	2985.5	2986.5	2988.5	2990.0	0000.0
	WELL LOCATION										
I	J	K	L	M	SHLT1	SHLB1	SHLT2	SHLB2	SHLT3	SHLB3	SHLT4



CARD 2

074	14	36	48	405	0000.0	0000.0	0000.0	-096.0	03.9	077.
	WELL LOCATION									
I	J	K	L	M	SHLB4	SHLT5	SHLB5	E1	RFM	TEMP



CARD 3

FIGURE 39

FORTRAN PROGRAMS

Fortran Program 1 (for programming, see Appendix L)

This program was designed to determine, sub-sea elevations to various markers, isopachs, sandstone isolith, sandstone-shale ratio and spontaneous potential reduction factor from input data.

Problem		Plan of Calculation
(A) Determine Sub-Sea elevations:	1.	A1 = COAL 1 - ELKB
	2.	A2 = COAL 2 - ELKB
	3.	A3 = BELRT - ELKB
	4.	A4 = BELRB - ELKB
	5.	A5 = TMLKR - ELKB
	6.	A6 = COLRT - ELKB
(B) Determine isopachs:	7.	SAND = BELRB - BELRT
	8.	A7 = BELRT - COAL 2
	9.	A8 = COLRT - COAL 2
	10.	A9 = COLRT - TMLKR
	11.	A10 = TMLKR - BELRT
(C) Determine sandstone isolith:	12.	SLTH = (BELRB - BELRT) - $\sum_1^5$ SHLB - SHLT
(D) Determine sandstone ratio:	13.	RATIO = $\frac{X-Y}{Y}$ where X = BELRB - BELRT and Y = $\sum_1^5$ SHLB - SHLT
(E) Convert observed RMF @ temperature TEMP to a fixed temperature @ 64°F.	14.	RMF1 = RFM x TEMP/64
(F) Standardize E1 to a standard mud filtrate of 5 ohm-m @ 64°F.	15.	E2 = E1 + K log RMF1/$_5$ where K = 73

(For comparing the spontaneous potential response of two or more wells, which in turn help in knowing the comparative shaliness, it is essential that the spontaneous potential be reduced

to a standard mud at a constant temperature, assuming the resistivity of formation water (Rw) to be constant. In the present study, a standard mud filtrate of 5 ohm-m resistivity at a constant temperature of 64°F is assumed and the observed spontaneous potentials are reduced to such standard (Wyllie, 1949).

If R_{mf1} is the resistivity of the mud filtrate in the bore hole at a standard temperature and E1 the observed spontaneous potential and let R_{mf2} be the resistivity of the standard mud filtrate and E2 the corresponding spontaneous potential, then assuming Rw to be a constant

$$E1 = -K \log \frac{R_{mf1}}{RW}$$

$$E2 = -K \log \frac{Rmf2}{RW}$$

$$\text{Therefore } E1 - E2 = K \log \frac{Rmf2}{Rmf1}$$

$$\text{and } E2 = E1 + K \log \frac{Rmf1}{Rmf2}$$

Thus from the above equation E2 is calculated for each well knowing E1 and Rmf1 from the bore hole at a constant temperature of 64°F and assuming Rmf2 to be 5 ohm-m at the same temperature.)

(G) Calculate spontaneous potential reduction factor (α) 16. ALPHA = E2/SSP where SSP = -120 millivolts

(Taking the value of Rw = 0.3 ohm-m @ 64°F, measured on the formation water recovered from the Cities Service Keystone 14-22 well (Lsd. 14, Sec. 22, Twp. 48, Rge. 4, W5 Mer.), a clean sandstone was expected to develop a static spontaneous potential (SSP) of -89 millivolts in a bore hole filled with mud of Rmf = 5 ohm-m @ 64°F, assuming the value of K = 73. However, for some reasons, under similar conditions, the Medallion Keystone 14-36 well (Lsd. 14, Sec. 36, Twp. 48, Rge. 4, W5 Mer.) which contain the cleanest sandstone, in the area, would develop a static spontaneous potential of -97 millivolts which is a little higher than the above calculated value of static spontaneous potential. To avoid such discrepancies, it was thought that an arbitrary value of -120 millivolts be chosen as static spontaneous potential and all the value of α be calculated from such standard.

It may be noted that the actual value of static spontaneous potential is not of much significance in the present study as long as it is equal to or greater than the maximum spontaneous potential observed in the bore hole. It is only the relative variations in the shaliness of the sandstones which was looked for in the spontaneous potential reductions factor map.)

Fortran Program 2 (for programming see Appendix M)

This program was assigned to calculate trend surfaces, (linear, quadratic and cubic) on the top of the Lea Park Shale, and the deviations from each one of these surfaces. A method of least squares power series analysis was used. The mathematical theory associated with such analysis is discussed in Appendix J.

The specific jobs assigned to the computer were as follows:

(A) 1. Calculate the value of linear surface at each observation point and the deviation from it.

2. Calculate the sum of squares of deviations from the linear surface.

(B) 3. Calculate the value of quadratic surface at each observation point and the deviation from it.

4. Calculate the sum of squares of deviations from the quadratic surface.

(C) 5. Calculate the value of cubic surface at each observation point and the deviation from it.

6. Calculate the sum of squares of deviations from the cubic surface.

Fortran Program 3 (for programming see Appendix N)

This program was designed to calculate shaliness (ms) of the basal Belly River sandstone. The equation 8., pp.105, was basically used in its determination.

To calculate the salinity of mud filtrate in ppm from resistivity of mud filtrate, a linear equation $\log_{Rmf1} = - \log_{ppm(Nacl)} + C$ was used, where $\log_{RMF1}$ is the logarithm of the resistivity of mud filtrate at a constant temperature of 64^0F, $\log_{ppm(Nacl)}$ is the logarithm of the

concentration in ppm of Nacl in mud filtrate and C is a constant. The value of C was determined from known values of log $_{RMF}$ and log $_{ppm(Nacl)}$ using diagram 3, Wyllie, 1957, and was found to be 3.80.

The value of m_{mf} in turn was calculated from the values of ppm. A constant value of m_w = 0.57 mol wts./liter solvent and K = 73 was used.

It is interesting to note that negative values of shaliness were obtained in wells where spontaneous potentials were poorly developed and underwent a reversal. The values of spontaneous potential in these wells are not reliable and consequently the corresponding values of ms were discarded.

<u>Fortran Program 4</u> (for programming see Appendix O)

This program was assigned to calculate the amount of variability accounted for by the linear, the quadratic and the cubic surface.

The amount of variation of a set of observations may be measured by the sum of the squares of the deviations from the mean. For fixed n, the sum of squares (S.S.) is a measure of the variation of that set of observations.

Let Xi = ith observation where i = 1 2,3,...... n

$\bar{X}$ = mean of n observations

$$\text{Then S.S.} = \sum_{i=1}^{n}(Xi - \bar{X})^2$$

$$= \Sigma Xi^2 - \frac{(\Sigma Xi)^2}{n}$$

In the present study, S.S. of the observed data and of the linear, the quadratic and the cubic surface were separately calculated. Following this, the ratio of the predicted to the observed variation was calculated.

DATA OUTPUT

Table VII illustrates the way in which the input data from the punched cards are printed out on a sheet of paper along with the answers of the various problems (A) to (G) relevant to Program 1.

No special training is required to read the computer results. The first three lines are a reproduction of the input data fed in the computer. The last three lines constitute the answers to the 16 problems.

Whenever all 16 answers are not possible because of the lack of input data, zeros are printed out instead. The values can be directly plotted on a base map according to the kind of contour map desired.

The output relevant to program 2, program 3 and program 4, not shown here, was self-explanatory.

TABLE VII

74	14	36	48	405	2646.0	2917.0	2938.0	2970.0	2992.0	3251.0	3465.0
					2976.0	2980.0	2985.5	2986.5	2988.5	2990.0	0.0
					0.0	0.0	0.0	-96.0	3.9	77.	
					271.0 A1	292.0 A2	324.0 A3	346.0 A4	605.0 A5	819.0 A6	22.0 (sand)
			(Ratio)		2.38	4.7 -97.8	.81	32.0 A7	527.0 A8	214.0 A9	281.0 A10
			(SLTH)		15.5	(RMF1) E2	$\propto$				

APPENDIX L

FORTRAN PROGRAM 1

```
..1    [illegible]
..L[illegible]
 25    READ 1,I,J,K,L,M,[illegible]
       READ 1,I,J,K,L,M,[illegible]
       READ 24,I,J,K,L,M,[illegible]
 1     FORMAT(1X,[illegible])
 24    FORMAT(1X,[illegible],F5.0)
       PUNCH 1,I,J,K,L,M,[illegible]
       PUNCH 26,SHLT1,SHLB1,SHLT2,SHLB2,SHLT3,SHLB3,SHLT4
       PUNCH 27,SHLB4,SHLT5,SHLB5,E1,RFM,TEMP
 26    FORMAT(17X,7F7.1)
 27    FORMAT(17X,4F7.1,F5.1,F5.0)
       IF(COAL1)3,3,4
 3     A1=0.0
       GO TO 5
 4     A1=COAL1-ELKB
 5     IF(COAL2)6,6,7
 6     A2=0.0
       A7=0.0
       A8=0.0
       GO TO 10
 7     A2=COAL2-ELKB
       A7=BELRT-COAL2
       IF(COLRT)8,8,9
 8     A8=0.0
       GO TO 10
 9     A8=COLRT-COAL2
 10    IF(TMLKR)11,11,12
 11    A5=0.0
       A9=0.0
       A10=0.0
       A6=0.0
       GO TO 13
 12    A5=TMLKR-ELKB
       A9=COLRT-TMLKR
       A10=TMLKR-BELRT
       A6=COLRT-ELKB
 13    SAND=BELRB-BELRT
       A3=BELRT-ELKB
       A4=BELRB-ELKB
       IF(SHLT1)14,14,15
 14    RATIO=0.0
       SLTH=0.0
       GO TO 16
 15    SHALE=SHLB1-SHLT1+SHLB2-SHLT2+SHLB3-SHLT3+SHLB4-SHLT4+SHLB5-SHLT5
       SLTH=SAND-SHALE
       RATIO=(SAND-SHALE)/SHALE
 16    IF(RFM)17,17,18
 17    RMF1=0.0
       E2=0.0
       ALPHA=0.0
       GO TO 19
 18    RMF1=(RFM*TEMP)/64.
       E2=E1+73.0*.434294*LOGF(RMF1/5.)
```

```
      ALPHA=[illegible]
19    PUNCH 20,[illegible]
      PUNCH 22,[illegible]
22    FORMAT(17X,[illegible])
      PUNCH 23,[illegible]
23    FORMAT(17X,[illegible])
      GO TO 2[illegible]
```

APPENDIX M

FORTRAN PROGRAM 2

```
2005
      DIMENSION IW(200),A(10,11),LR(10),LC(10),VAL(200)
      DIMENSION X(200),Y(200),D(200),C(10,11),R(200)
      AITH=1./8.
      READ50,NO
50    FORMAT(I4)
      DO100 I=1,NO
      READ62,IW(I),LSD,ISECT,TWNS,RNG,ELKB,BELRB
 62   FORMAT(I4,2I3,F3.0,F2.0,2X,F7.1,21X,F7.1)
      READ304
304   FORMAT(I1)
      READ304
      TEMP1=(ISECT-1)/6
      TEMP2=(LSD-1)/4
      Y(I)=(TWNS-47.)*6.+TEMP1+TEMP2/4.+AITH
      SECT=ISECT-((ISECT-1)/12)*12
      IF(SECT-6.)63,63,64
63    SECT=SECT-1.
      GO TO 65
64    SECT=12.-SECT
65    SDL=LSD-((LSD-1)/8)*8
      IF(SDL-4.)66,66,67
66    SDL=SDL-1.
      GO TO 68
67    SDL=8.-SDL
68    X(I)=30.-SDL/4.-SECT-6.*RNG-AITH
100   D(I)=BELRB-ELKB
      DO220 I=1,10
      DO220 J=I,11
220   C(I,J)=0.
      DO120 I=1,10
      DO120 J=I,10
      NK=0
      N=1
73    NK=NK+N
      IF(NK-I)72,69,69
72    N=N+1
      GO TO 73
69    L=NK-I
      M=N-L-1
      NK=0
      N=1
74    NK=NK+N
      IF(NK-J)77,76,76
77    N=N+1
      GO TO 74
76    L=L+NK-J
      M=M+N-NK+J-1
      DO120 K=1,NO
      IF(I-1)78,78,120
78    C(J,11)=C(J,11)+D(K)*(X(K)**L)*(Y(K)**M)
120   C(I,J)=C(I,J)+(X(K)**L)*(Y(K)**M)
      DO230 I=2,10
      I1=I-1
```

```
      DO 230 J=1,I1
230   C(I,J)=C(J,I)
      N=1
      KK=2
260   N=N+KK
      KK=KK+1
      M=N+1
      DO243 I=1,N
      DO243 J=1,N
243   A(I,J)=C(I,J)
      DO241 I=1,N
241   A(I,M)=C(I,11)
      IF(N-6)51,52,53
51    PUNCH 302
302   FORMAT(//11H     MATRIX)
      PUNCH 54,((A(I,J),J=1,M),I=1,N)
54    FORMAT(1X,4E16.8)
      GO TO 3
52    PUNCH 390
390   FORMAT(//11H1    MATRIX)
      PUNCH55,((A(I,J),J=1,M),I=1,N)
55    FORMAT(1X,4E16.8/1X,3E16.8)
      GO TO 3
53    PUNCH 390
      PUNCH56,((A(I,J),J=1,M),I=1,N)
56    FORMAT(1X,4E16.8/1X,4E16.8/1X,3E16.8)
 3    KZ=1
      DO 16 K=1,N
      LR(K)=K
      LC(K)=K
      I=K
      IZ=K
      P=A(K,K)
      DO 5 J=K,N
      DO 5 JZ=K,N
      IF(ABSF(P)-ABSF(A(J,JZ)))4,5,5
4     P=A(J,JZ)
      I=J
      IZ=JZ
5     CONTINUE
      IF(I-K)6,6,23
6     IF(IZ-K)7,7,18
 7    IF(A(K,K))12,8,12
8     PRINT 10
      PUNCH 10
10    FORMAT(24H THE MATRIX IS SINGULAR.)
      GO TO 32
12    P=1.0/A(K,K)
      A(K,K)=1.0
      DO 13 J=1,M
13    A(K,J)=P*A(K,J)
      DO 16 I=1,N
      IF(K-I)14,16,14
14    B=A(I,K)
```

```
      A(I,K)=0.0
      DO 15 J=1,M
 15   A(I,J)=A(I,J)-B*A(K,J)
 16   CONTINUE
      KZ=0
      K=N
      DO 26 IA=1,N
      IF(LR(K)-K)17,21,17
 17   IZ=LR(K)
C     CHANGE COLUMNS IZ AND K
 18   DO 19 J=1,N
      TS=A(J,IZ)
      A(J,IZ)=A(J,K)
 19   A(J,K)=TS
      IF(KZ)20,21,20
 20   LC(K)=IZ
      GO TO 12
 21   IF(LC(K)-K)22,26,22
 22   I=LC(K)
C     CHANGE ROWS I AND K
 23   DO 24 J=1,M
      TS=A(I,J)
      A(I,J)=A(K,J)
 24   A(K,J)=TS
      IF(KZ)25,26,25
 25   LR(K)=I
      GO TO 6
 26   K=K-1
      PUNCH303
 303  FORMAT(//12H      INVERSE)
      IF(N-6)87,58,59
 87   PUNCH54,((A(I,J),J=1,M),I=1,N)
      GO TO 48
 58   PUNCH55,((A(I,J),J=1,M),I=1,N)
      GO TO 48
 59   PUNCH56,((A(I,J),J=1,M),I=1,N)
 48   SSR=0.
      PUNCH151
 151  FORMAT(//34H  WELL   CALC. VALUE       RESIDUAL)
      DO310 I=1,NO
      VAL(I)=A(1,M)+A(2,M)*X(I)+A(3,M)*Y(I)
      IF(N-6)280,290,290
 280  R(I)=D(I)-VAL(I)
      PUNCH57,IW(I),VAL(I),R(I)
 57   FORMAT(I5,2E16.8)
      GO TO 310
      XI=X(I)
      YI=Y(I)
 290  VAL(I)=VAL(I)+A(4,M)*XI**2    +A(5,M)*XI*YI     +A(6,M)*YI**2
      IF(N-6)280,280,300
 300  AA=VAL(I)+A(7,M)*X(I)**3+A(8,M)*X(I)*X(I)*Y(I)
      VAL(I)=AA+A(9,M)*X(I)*Y(I)*Y(I)+A(10,M)*Y(I)**3
      GO TO 280
 310  SSR=SSR+R(I)*R(I)
```

```
      IF(N-6)321,322,322
321   PUNCH152
152   FORMAT(//28H SUM OF SQUARES OF RESIDUALS)
      S1=SSR
      PUNCH330,SSR
330   FORMAT(5X,E16.8)
      GO TO 324
322   PUNCH153
153   FORMAT(//47H SUM OF SQUARES OF RESIDUALS  REDUCT OF SQUARES)
      REDSQ=S1-SSR
      S1=SSR
      PUNCH323,SSR,REDSQ
323   FORMAT(5X,E16.8,8X,E16.8)
324   IF(N-6)260,260,380
380   STOP
32    IF(N-6)260,260,380
      END
```

APPENDIX N

FORTRAN PROGRAM 3

```
      C=1./LOGF(10.)
3     READ 1,IW,E1,RMF1
1     FORMAT(I4//38X,F7.1//23X,F5.1)
      READ 7,A
7     FORMAT(18X,F5.1)
      IF(E1)4,3,4
4     IF(RMF1)5,3,5
5     RMF1=LOGF(RMF1)*C
      PPM=3.80-RMF1
      PPM=10.**PPM
      FLMOL=PPM*.00001724
      E1=E1*(-.01369863)
      ANTLG=10.**E1
      SM=(2.15*(0.57-FLMOL*ANTLG))/(ANTLG-1.)
      PUNCH 2,IW,SM
2     FORMAT(1X,I5,5X,5H MS =,E16.8)
      GO TO 3
      END
```

APPENDIX O

FORTRAN PROGRAM 4

```
      DIMENSION SS(4)
      DO 27 K=1,4
      READ 2,N
2     FORMAT(1X,I5)
      SUMX=0.
      SUMXX=0.
      DO 3 I=1,N
      IF(K-1)5,5,4
5     READ 6,X
6     FORMAT(///38X,F7.1)
      READ 50,A,B
50    FORMAT(18X,F5.1/18X,F5.1)
      GO TO 7
4     READ 8,X
8     FORMAT(5X,E16.8)
7     SUMX=SUMX+X
3     SUMXX=SUMXX+X*X
      TN=N
      SS(K)=SUMXX-SUMX*SUMX/TN
      GO TO(26,20,21,22),K
26    PUNCH 11
11    FORMAT(1X,14H ORIGINAL DATA)
      GO TO 27
20    PUNCH 23
23    FORMAT(1H0,17H TREND FOR LINEAR)
      GO TO 27
21    PUNCH 24
24    FORMAT(1H0,20H TREND FOR QUADRATIC)
      GO TO 27
22    PUNCH 25
25    FORMAT(1H0,16H TREND FOR CUBIC)
27    PUNCH 9,SS(K)
9     FORMAT(1X,7H S.S. =,E16.8)
      DO 16 K=2,4
      PV=SS(K)*100./SS(1)
      IF(K-3)13,14,17
13    PUNCH 15,PV
15    FORMAT(1H0,33H PERCENT VARIABILITY FOR LINEAR =,F6.2)
      GO TO 16
14    PUNCH 18,PV
18    FORMAT(1X,36H PERCENT VARIABILITY FOR QUADRATIC =,F6.2)
      GO TO 16
17    PUNCH 19,PV
19    FORMAT(1X,32H PERCENT VARIABILITY FOR CUBIC =,F6.2)
16    CONTINUE
      END
```

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UCTURAL CR

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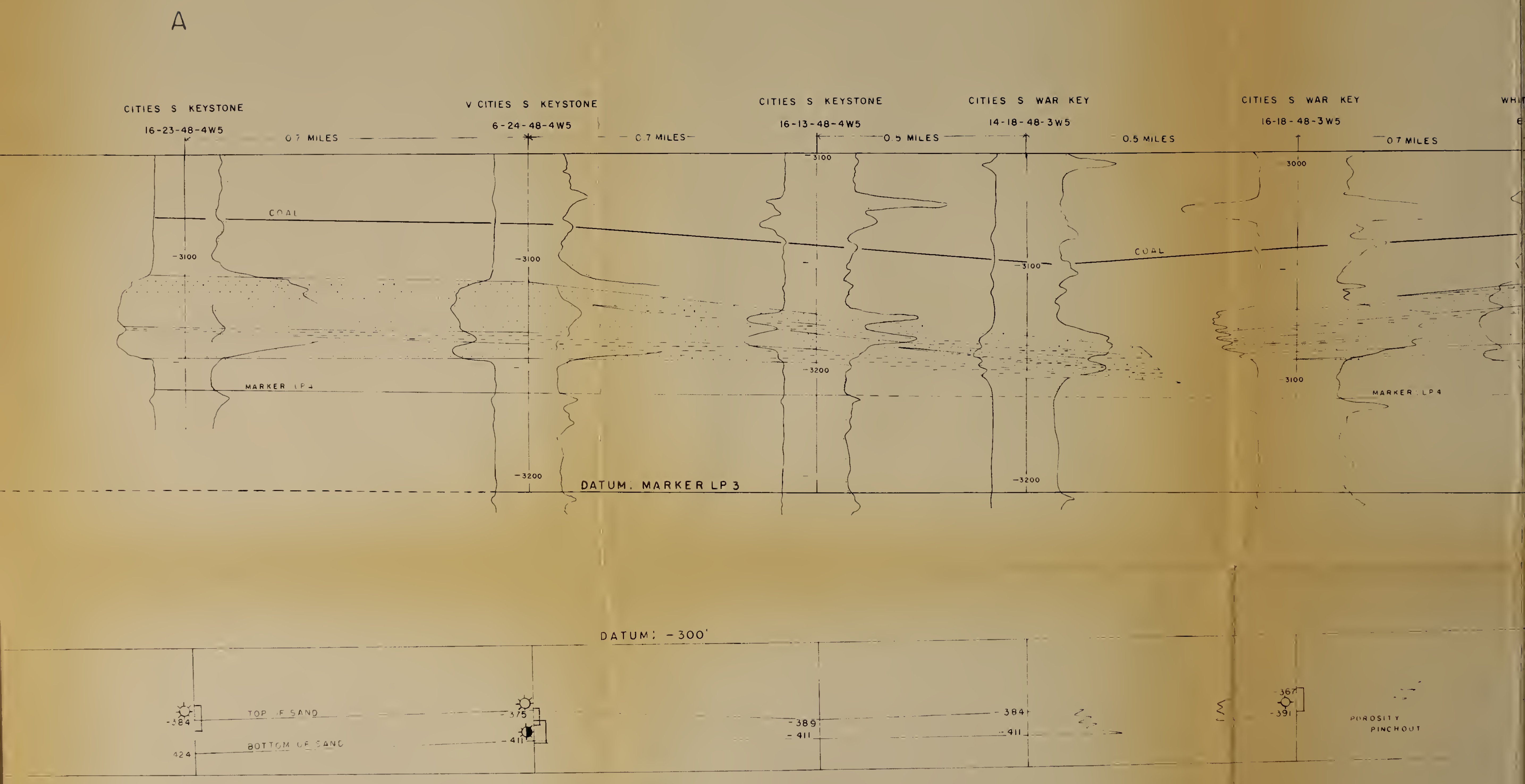
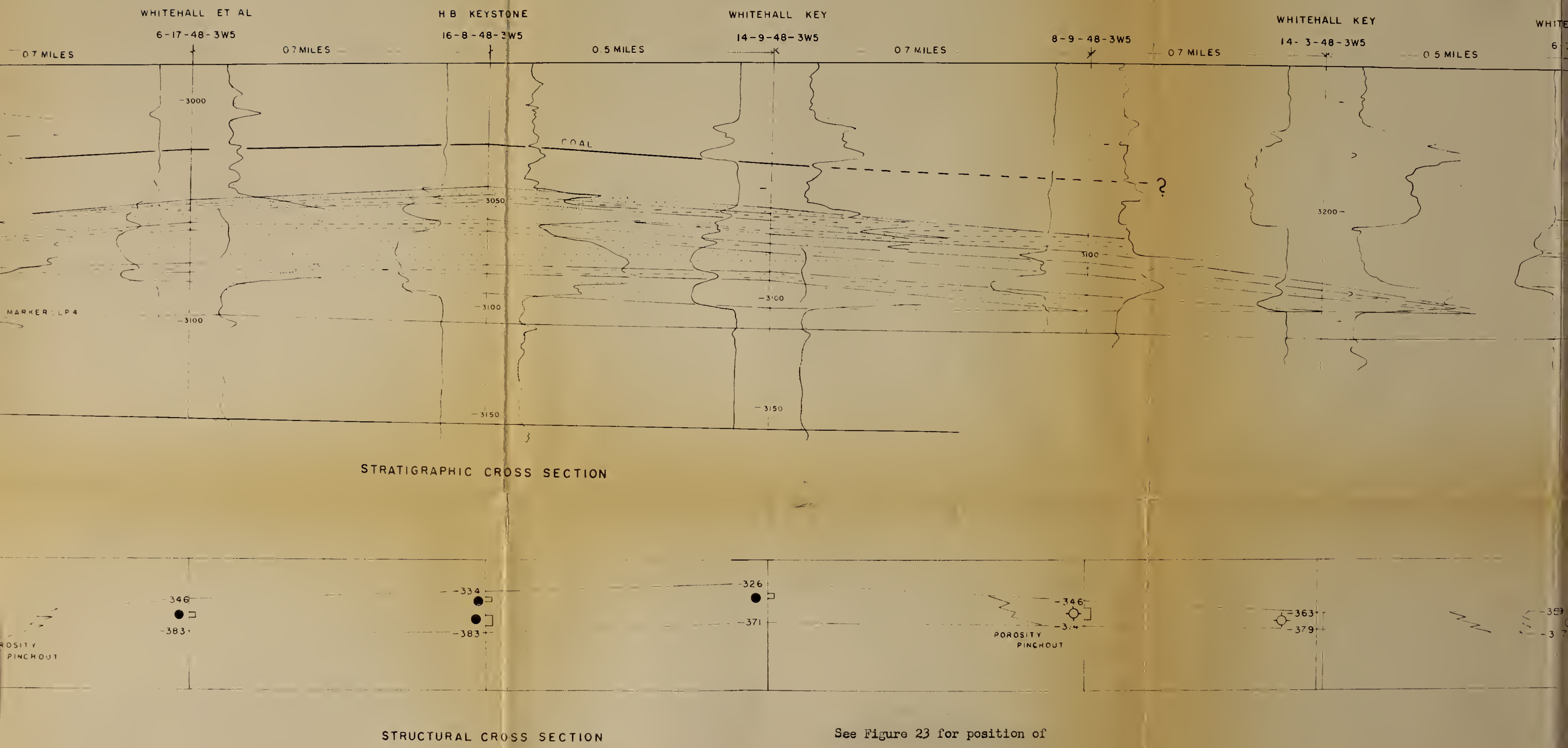


FIGURE 24 Cross se
in the t



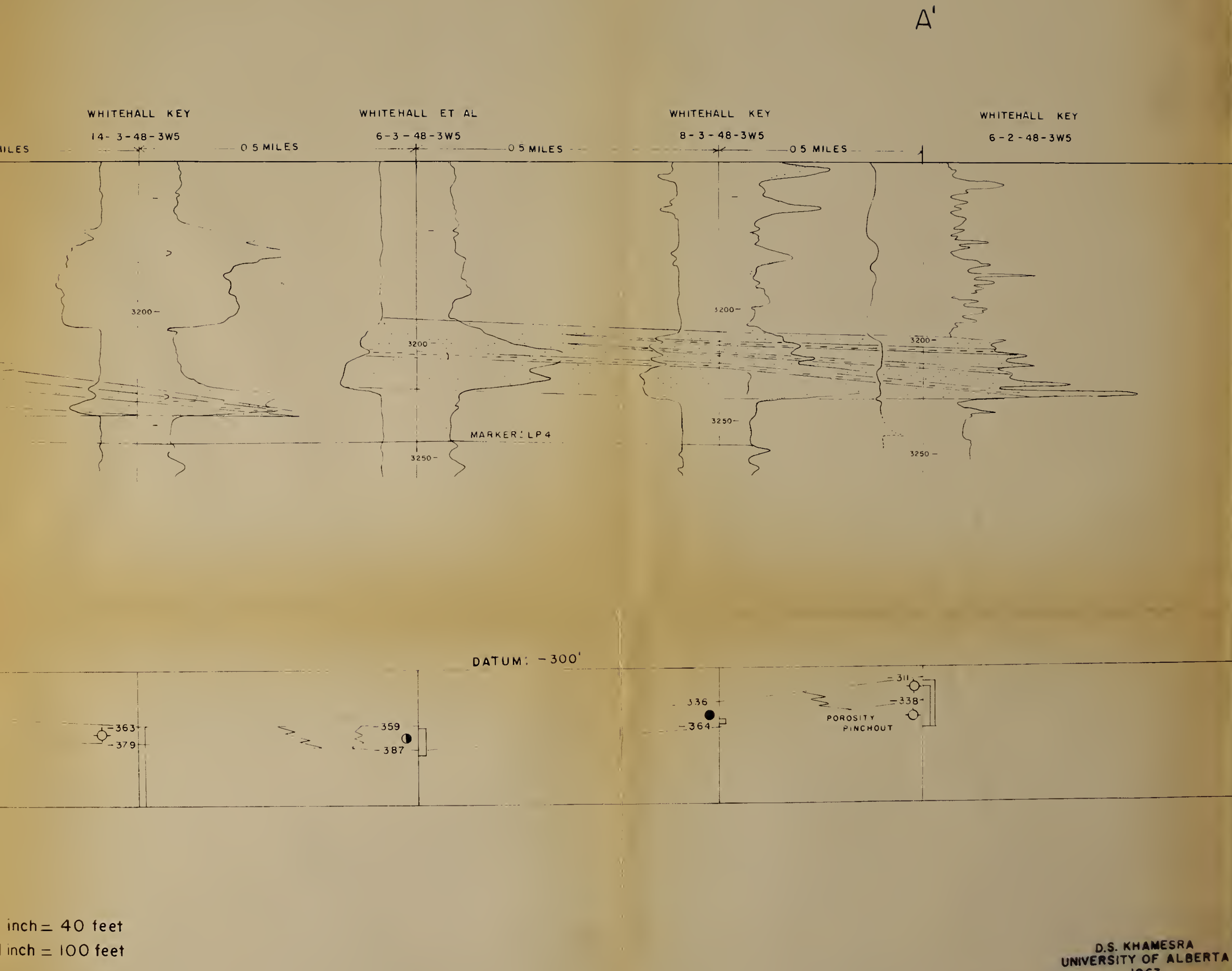
See Figure 23 for position of cross sections

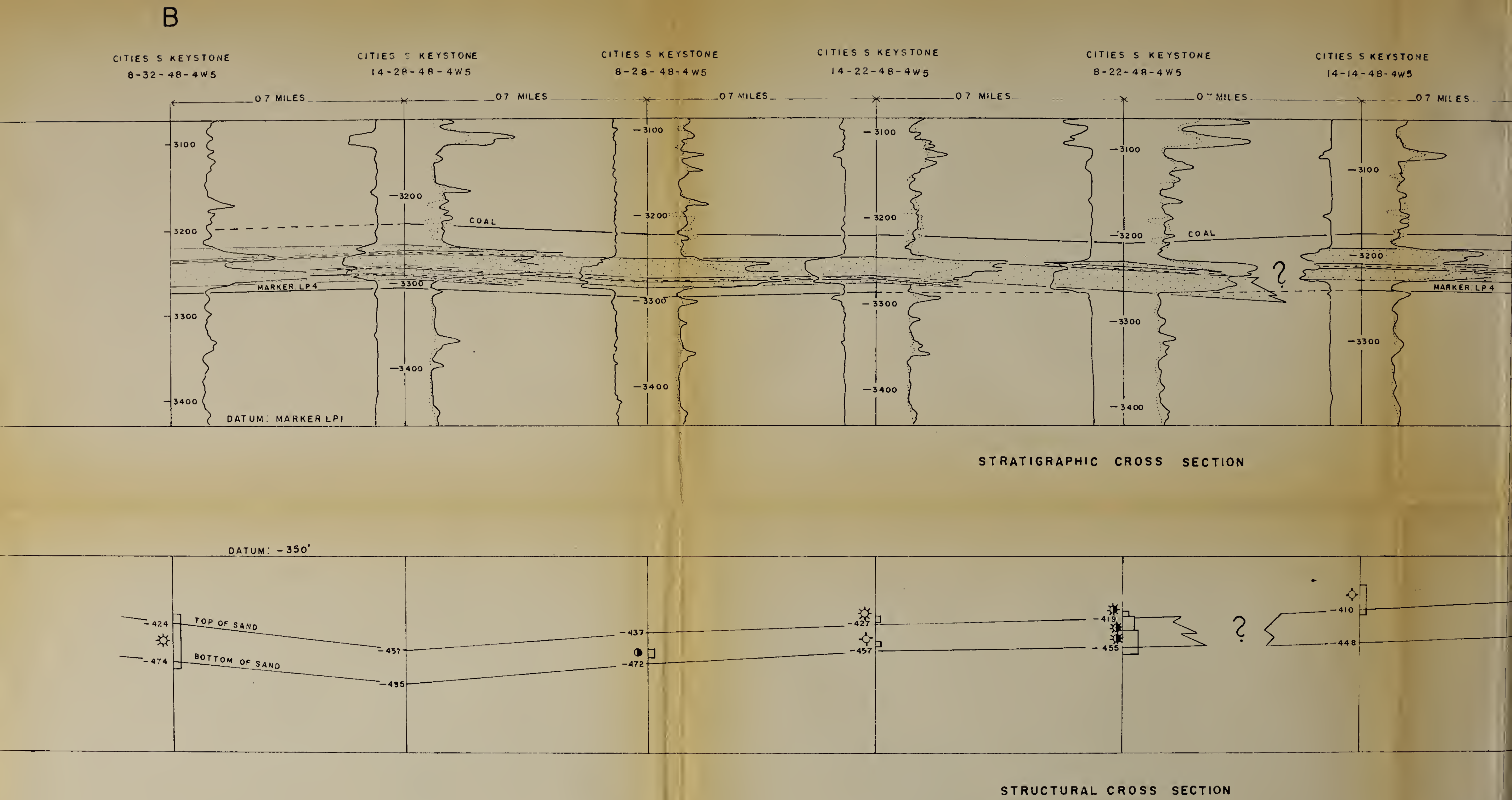
FIGURE 24 Cross sections along A A' showing configuration of sandstone bodies in the basal Belly River sandstone.

Legend: See Figure 23

Vertical Scale: Stratigraphic Section 1 inch = 40 feet

Structural Section 1 inch = 100 feet

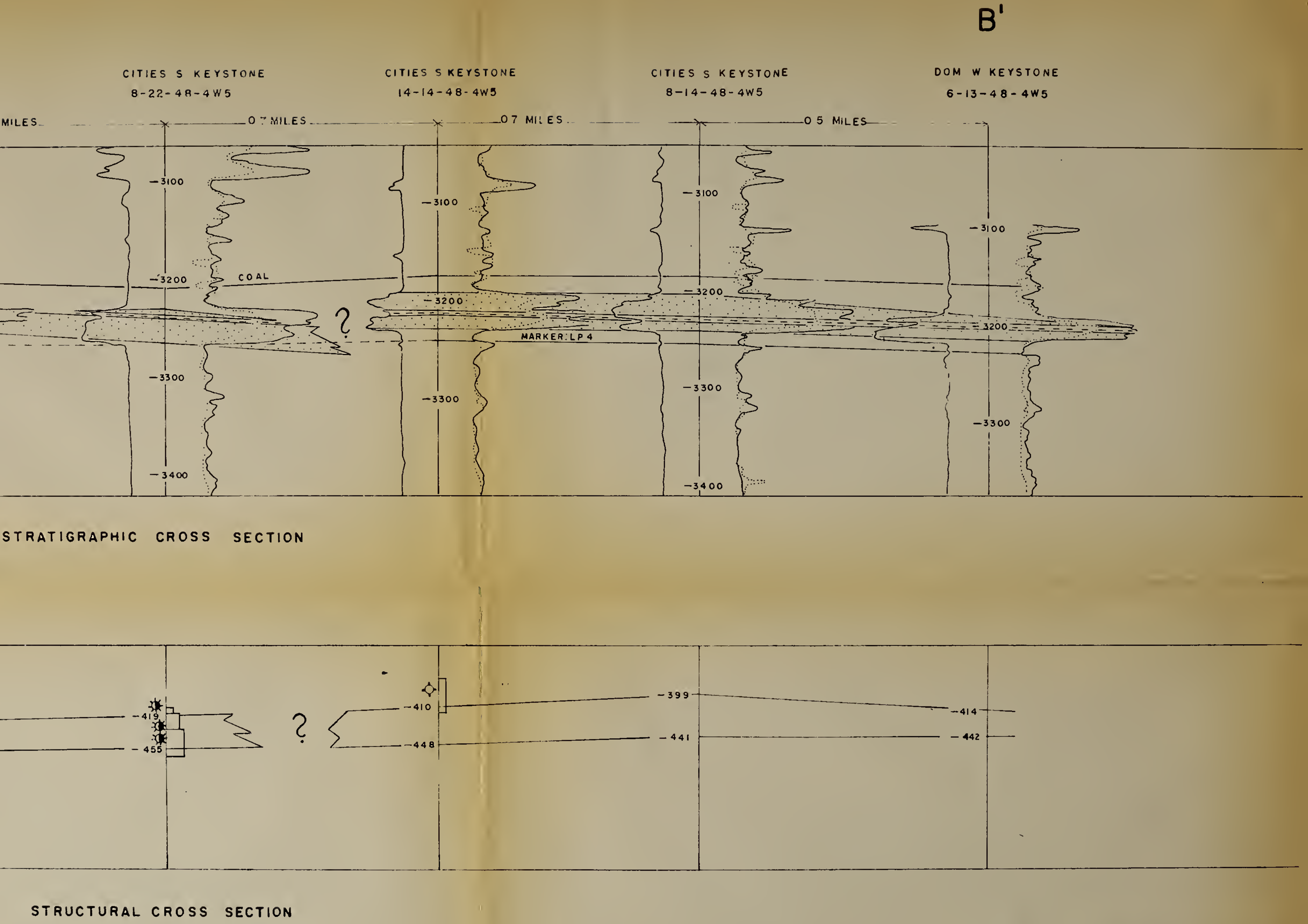

A'
WHITEHALL KEY
14- 3-48-3W5
WHITEHALL ET AL
6-3-48-3W5
WHITEHALL KEY
8-3-48-3W5
WHITEHALL KEY
6-2-48-3W5
ILES
0 5 MILES
0 5 MILES
0 5 MILES
3200
3250
MARKER: LP4
DATUM: -300'
-363
-379
-359
-387
336
-364
-311
-338
POROSITY
PINCHOUT
inch = 40 feet
1 inch = 100 feet
D.S. KHAMESRA
UNIVERSITY OF ALBERTA
1963



See fig

FIGURE 26
CROSS SECTIONS ALONG B--B'

Legend See Fig
Vertical Scale



See figure 23 for position of cross sections

FIGURE 26
CROSS SECTIONS ALONG B--B'

Legend See Figure 23

Vertical Scale: Stratigraphic Section 1 inch = 100 feet
Structural Section 1 inch = 100 feet

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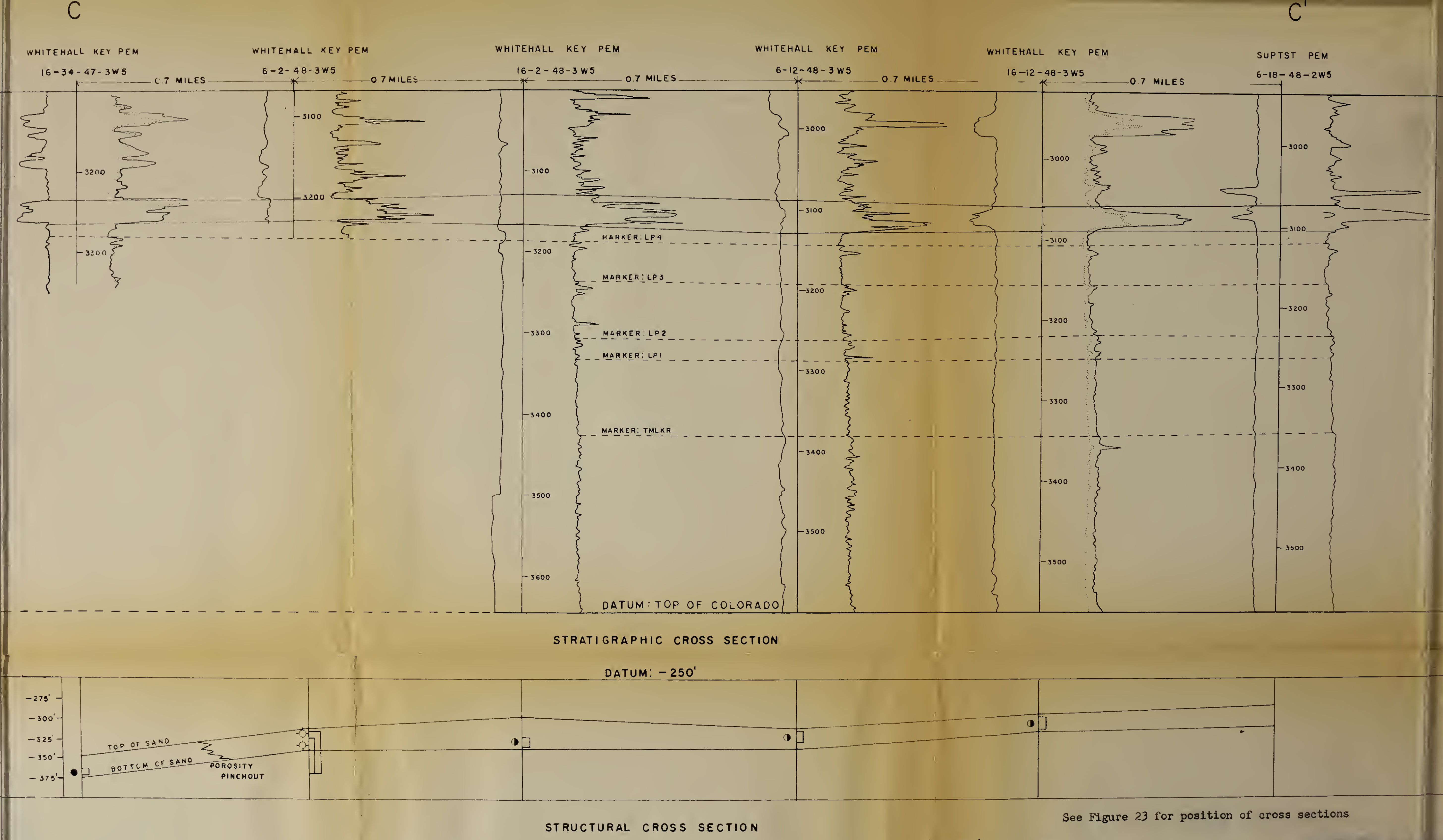

See Figure 23 for position of cross sections

FIGURE 27: Cross sections along CC' showing different markers in Colorado and Lea Park Shale used in this study.

Legend: See Figure 23

Vertical Scale: Stratigraphic Section 1 inch = 100 feet

Structural Section 1 inch = 100 feet

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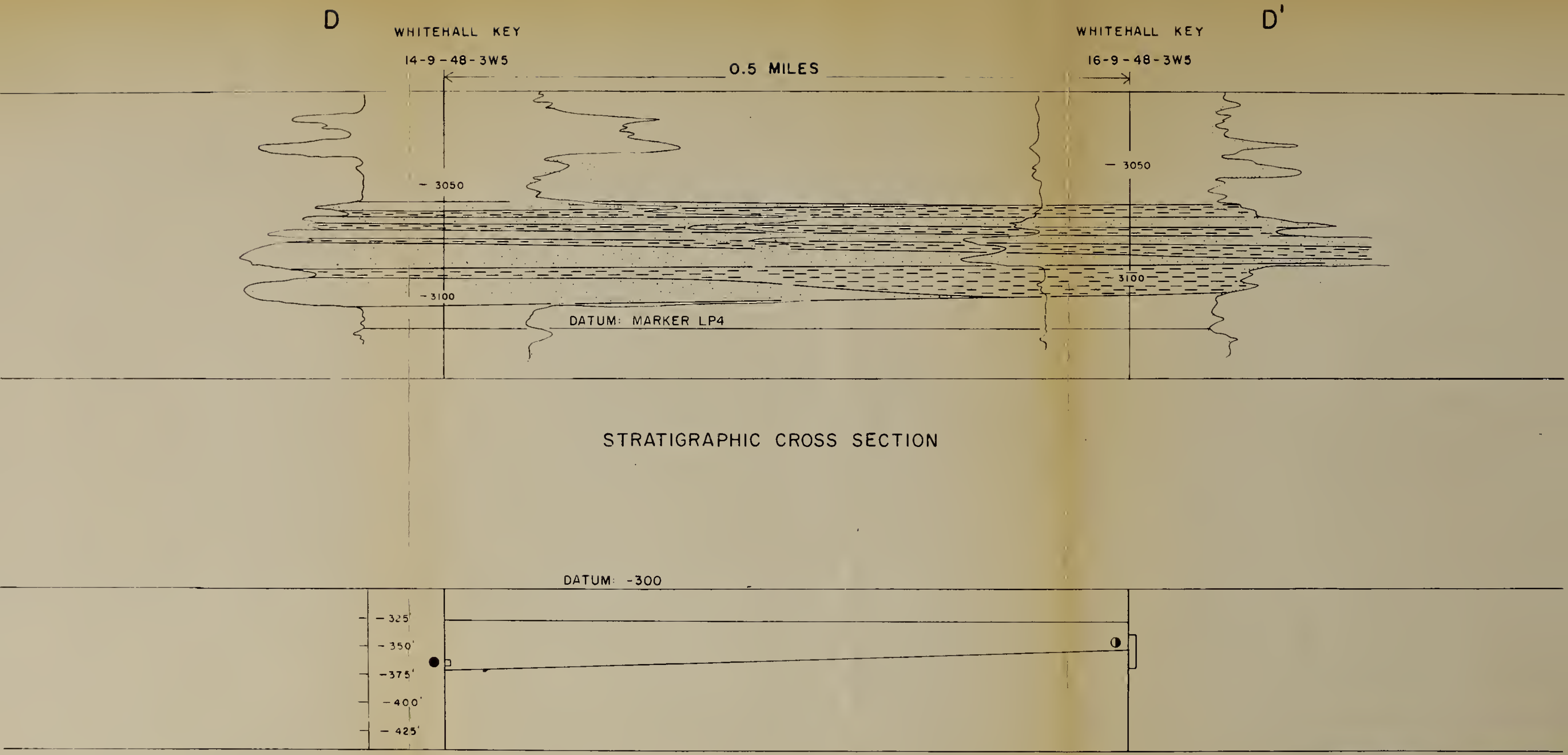

STRUCTURAL CROSS SECTION

FIGURE 28

CROSS SECTIONS ALONG D—D'

See Figure 23 for position of cross sections

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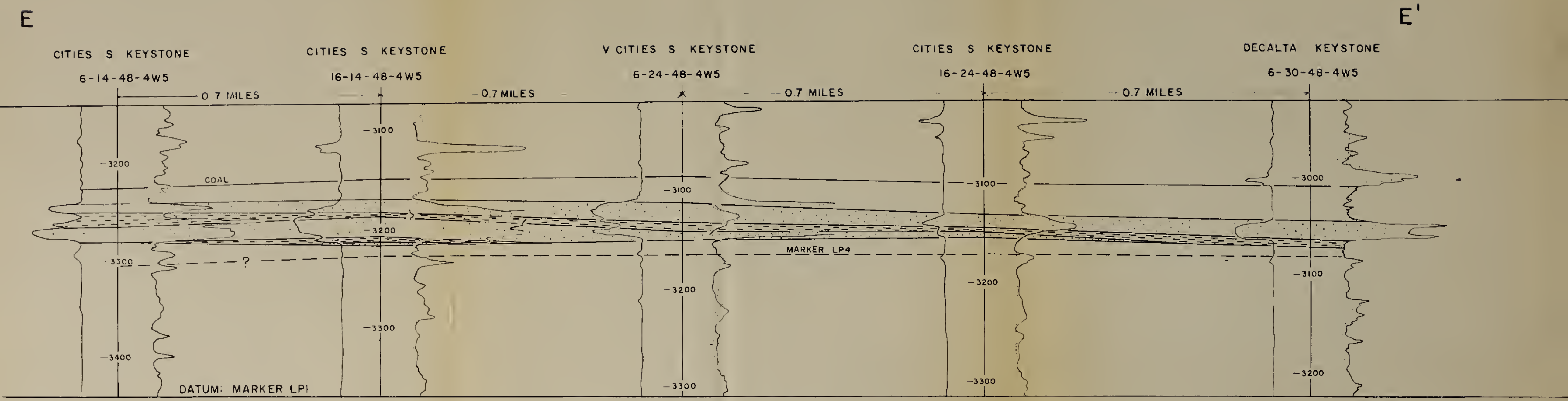
1963

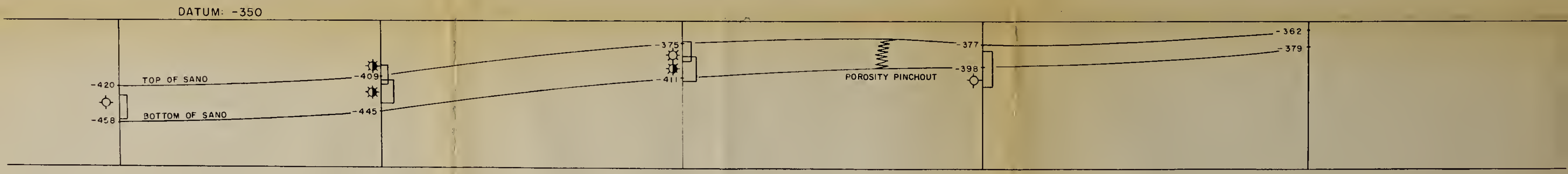
Legend: See Figure 23

Vertical Scale: Stratigraphic Section 1 inch = 50 feet

Structural Section 1 inch = 100 feet



STRATIGRAPHIC CROSS SECTION



STRUCTURAL CROSS SECTION

See Figure 23 for positions of cross sections

FIGURE 29

CROSS SECTIONS ALONG E-E'

Legend: See Figure 23

Vertical Scale: Stratigraphic Section 1 inch = 100 feet

Structural Section 1 inch = 100 feet

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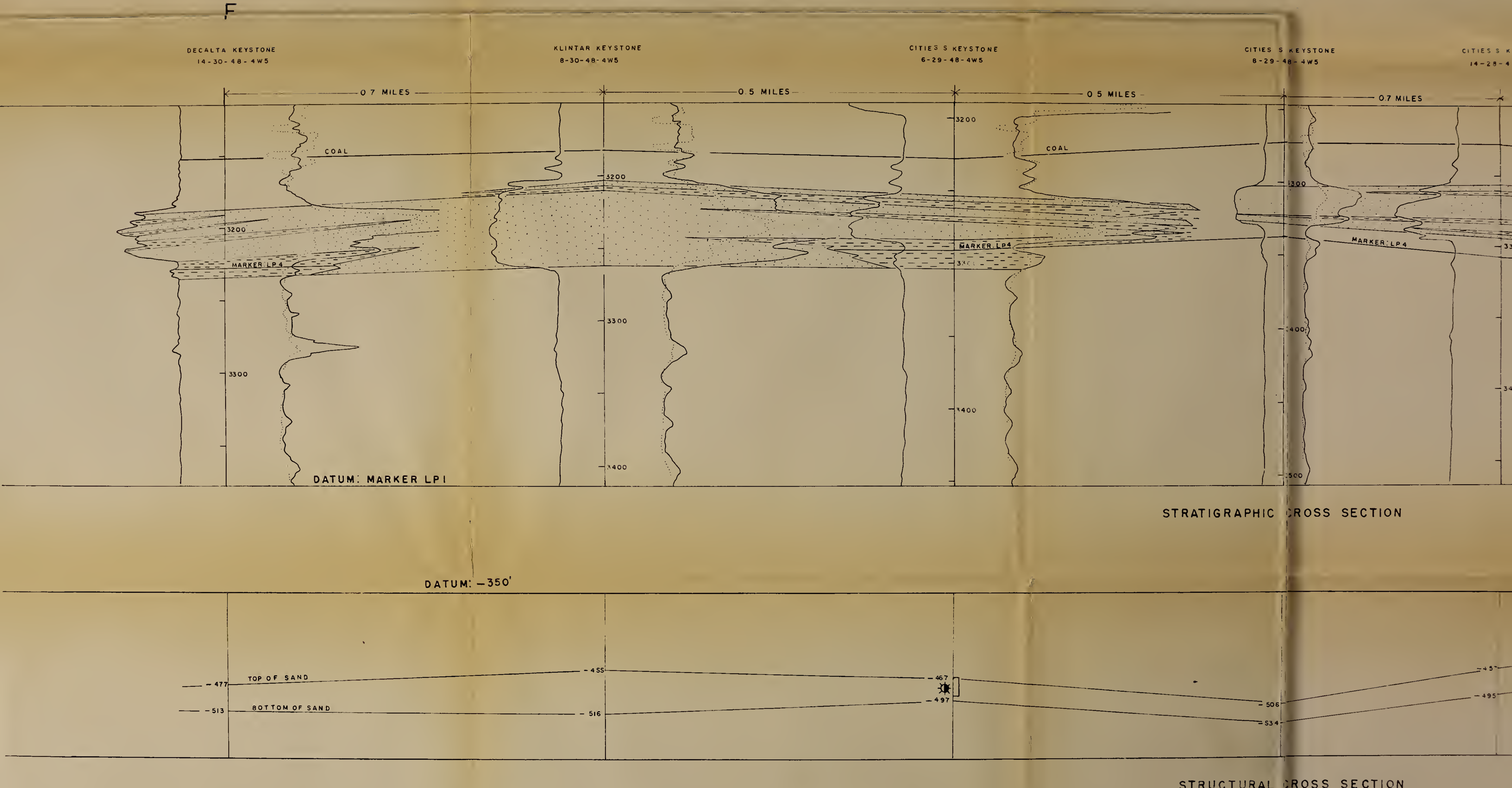
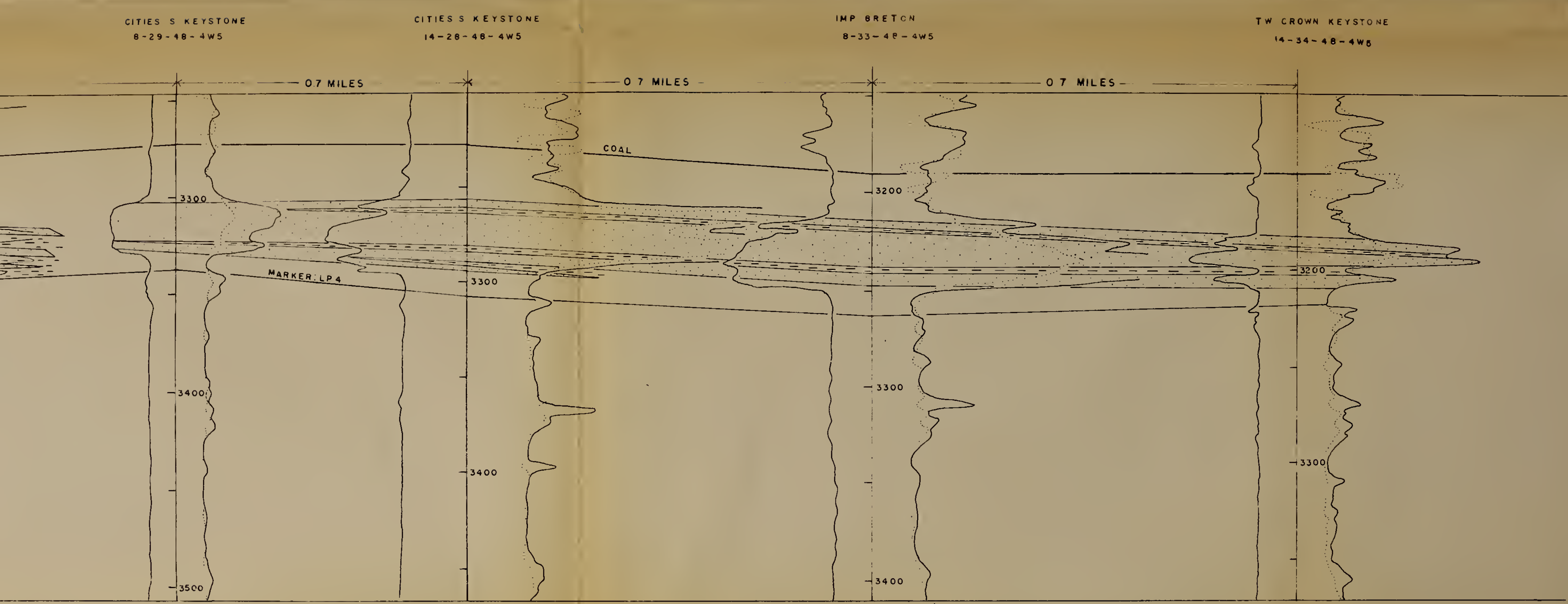
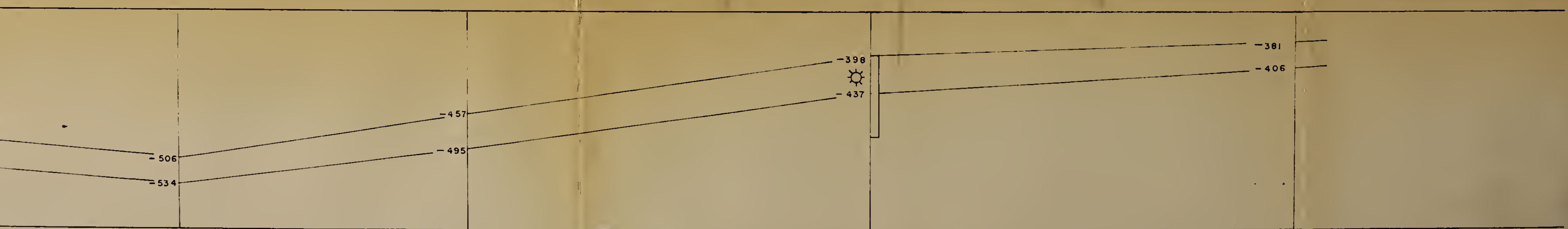


FIGURE 30
CROSS SECTIONS ALONG F-F'

F'



STRATIGRAPHIC CROSS SECTION



STRUCTURAL CROSS SECTION

See Figure 23 for positions of cross sections

FIGURE 30

CROSS SECTIONS ALONG F-F'

Legend: See Figure 23

Vertical Scale: Stratigraphic Section 1 inch = 50 feet

Structural Section 1 inch = 100 feet

D.S. KHAMESRA
UNIVERSITY OF ALBERTA
1963